Department of Electrical Engineering and Automation

Outdoor lighting - Mesopic photometry, adaptation conditions and user preferences in pedestrian way lighting

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Aalto University

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Outdoor lighting - Mesopic photometry, adaptation conditions and user preferences in pedestrian way lighting

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Abstract

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Abstract

The starting point of this work is to review the current recommendations and criteria of road and pedestrian way lighting. At present, the emphasis of traffic safety, the increasing energy costs, and improvements in mesopic photometry have led to new discussions about the accuracy of the recommendations for road lighting. Sufficient road lighting is generally based on the lighting requirements given in different lighting classes.

For road lighting, the value of 2 cd/m^2 is recommended as the minimum average road surface luminance for the highest lighting class in the CIE and CEN publications. The basis of the average road surface luminance for the lower lighting classes is unknown and lacks experimental works. Moreover, the experimental set-ups of the studies conducted in the 1930s and 1950s do not meet the conditions of motor traffic lighting nowadays. They also have deficiencies in the number and age distributions of the subjects. The values of the average horizontal illuminances of the pedestrian way lighting recommendations are based on studies conducted in the 1970s and 1980s. However, no information exists on how the recommended illuminance values are derived for the different lighting classes.

The current recommendations for outdoor lighting are based on photopic photometry, this is daylight visibility conditions. In outdoor lighting, the luminances are in the mesopic range. The CIE recommended system for mesopic photometry should be used in providing recommendations and criteria for both road and pedestrian way lighting. Before implementing mesopic photometry, the adaptation luminance of the road users should be known. This study examined the adaptation conditions of pedestrians based on eye-tracking measurements. A case study in a pedestrian way was conducted in Chongqing of China. The study is related to the currently ongoing task of the CIE JCT-1 Implementation of CIE 191 System for Mesopic Photometry in Outdoor Lighting, which is to investigate adaptation and viewing conditions and define visual adaptation fields in outdoor lighting. The case study consisted of eye-tracking measurements and subjective evaluations of the lighting conditions.

It was found that the eye-fixation areas and locations were around a central area of the road surface in the horizontal level but spread over a wider area in the vertical level. The subjective importance of facial recognition depends on the specific visual tasks at different light levels in a pedestrian way. The results also suggest that further studies using an eye-tracking system could combine eye-fixation data with pupil size and luminance data. This would help in further analysis of visual adaptation fields of the road users.

Keywords lighting criteria, road lighting, pedestrian way lighting, system of mesopic system, visual adaptation field, eye-tracking system

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Espoo, 27 May 2014
Wei Luo

Contents

List of Abbreviations and Symbols

Abbreviations

AOIs	areas of interest
BSI	British Standard Institute
CABR	China Academy of Building Research
CEN	Comité Européen de Normalisation,
	European Committee for Standardization
CFL	compact fluorescent lamp
CIE	Commission International de l'Éclairage
	International Commission on Illumination
CMH	ceramic metal halide
CRI	colour rendering index
DEN	Danish Norm
EN	European Norm
FGS	Forschungsgesellschaft für das Strassenwesen
	Research Society of Highways in Germany
HPM	high pressure mercury
HPS	high pressure sodium
ILE	Institution of Lighting Engineers
JTC	Joint Technical Committee
LED	light emitting diode
LPS	low pressure sodium
MH	metal halide

MOC	Ministry of Construction in China
NEN	Dutch Norm
NNI	Nederland Normalisatie Instituut
	Netherlands Standardization Institute
NSVV	De Nederlandse Stichting Voor Verlichtingskunde
	The Dutch Foundation for Illumination
SAE	Society of Automotive Engineers
SPD	spectral power distribution
SMI	SensoMotoric Instruments
TC	Technical Committee
UFOV	useful field of view

Symbols

B	background brightness
$\bar{B}$	average luminance [cd/m²]
CCT	correlated colour temperature [K]
$E_{h,av}$	average horizontal illuminance [lx]
$E_{h,min}$	minimum horizontal illuminance [lx]
$E_{hs,av}$	average hemispherical illuminance [lx]
$E_{v,min}$	minimum vertical illuminance [lx]
$E_{sc,min}$	minimum semi-cylindrical illuminance [lx]
F	ratio of (L_{ave}-L_o) to L_{ave}
G	glare classes
L_{ave}	average road surface luminance [cd/m²]
L_{max}	maximum average road surface luminance [cd/m²]
L_{min}	minimum average road surface luminance [cd/m²]
$\bar{L}$	mean road surface luminance [cd/m²]
L_o	object luminance [cd/m²]

$V(\lambda)$	CIE photopic spectral luminous efficiency function
$V'(\lambda)$	CIE scotopic spectral luminous efficiency function
S/P-ratio	ratio of scotopic to photopic luminous output
SR	surround ratio
TI	threshold increment [%]
T_i	values for each question in the range of [-2, -1, 0, 1, 2]
U	uniformity
U_l	longitudinal uniformity of road surface luminance
U_o	overall uniformity of road surface luminance
	overall uniformity of hemispherical illuminance
R_a	CIE CRI
$VE_{\bar{B}}$	average evaluation of the luminance level
V	evaluation value
W_i	number of subject who chose the according value (T_i)

List of Publications

I. Luo, Wei; Puolakka, Marjukka; Viikari, Meri; Kufeoglu, Sinan; Ylinen, Anne; Halonen, Liisa. 2012. Lighting criteria for road lighting: a review. *Light& Engineering*.vol.20, No.4, pp.64-74.

II. Luo, Wei; Puolakka, Marjukka; Halonen, Liisa. 2012. Mesopic photometry: The CIE 191 system based on visual performance. *China Illuminating Engineering Journal*, vol.7, No.1, pp.11-14.

III. Luo, Wei; Puolakka, Marjukka; Halonen, Liisa. 2012. Outdoor lighting- considerations of mesopic photometry and light source SPD, *China Illuminating Engineering Journal*, vol.7, No.1, pp.29-32.

IV. Puolakka, Marjukka; Cengiz, Can; Luo, Wei; Halonen, Liisa. 2012. Implementation of CIE 191 mesopic photometry-ongoing and future actions, In: *Proceedings of CIE 2012 Lighting Quality & Energy Efficiency*, Hangzhou, China, pp.64-70.

V. Luo, Wei; Puolakka, Marjukka; Zhang, Qingwen; Yang, Chunyu; Halonen, Liisa. 2013. Pedestrian way lighting: user preferences and eye-fixation measurements, *Journal of Lighting Engineering,* vol.15, No.1, pp.19-34.

Author's Contribution

The author has played a major role at all stages of the work presented in this thesis. The author was responsible for four publications as the main author. In the review publication (Publication I), the author collected the information and reviewed all the previous studies. In the other three publications (Publication II, III and V), the author collected the information, conducted the experiments and analyzed the data. In addition, the author was responsible for one publication as the co-author (Publication IV). Some of the formation presented in Publication IV was collected by the author.

1. Introduction

1.1 Background

Photometry is defined by the International Commission on Illumination (CIE) as 'the measurement of quantities referring to radiation as evaluated according to a given spectral luminous efficiency function, e.g. $V(\lambda)$ or $V'(\lambda)$' [1]. Systems for mesopic photometry have been developed based on two visual criteria: brightness matching and visual performance. Until the mid-1990s, most of the visual research on developing a system for mesopic photometry concentrated on using brightness matching as the visual criterion [2]. With brightness matching, two adjacent fields are compared in terms of their comparative brightness [3]. Towards the end of the 1990s, interest in developing mesopic photometry based on visual performance increased. With this approach, visual performance measures relevant to real-life situations are used to define the spectral sensitivity functions [2]. Visual assessments are conducted in real-life situations, such as driving at night, including the measures regarding whether an object can be seen, how quickly it can be seen, and identification of the object [4]. These visual assessments initiated the development of a system for visual performance based mesopic photometry. In 2010, the CIE 191: 2010 *Recommended System for Mesopic Photometry Based on Visual Performance* [2] was published by the CIE. This report provides an international basis for lighting units, products and measurements at low light levels.

Along with the development of mesopic photometry, the increasing costs of energy and environmental concerns have led to discussions on the need to redefine the current outdoor lighting recommendations. Road lighting design is generally based on lighting requirements given for different road lighting classes. In Europe, the lighting requirements are quantified by the controlling criteria given in the CIE and CEN (Comité Européen de Normalisation) publications [5–10]. The lighting classes are generally selected and characterised on the basis of road classification, which include several influencing parameters, such as traffic volume and environmental conditions [I].

The lighting criteria for motor traffic include road surface luminances, luminance distribution, limitation of glare, and lighting of the surroundings of the road. The lighting of the road surface is evaluated based on the average road surface luminance (L_{ave}), the overall uniformity of the luminance (U_o) and the longitudinal uniformity of the luminance (U_l). The limitation of glare, in particular disability glare, is evaluated using the threshold increment (*TI*). The lighting of the surroundings of the road is evaluated using the surround ratio (*SR*) [5, 7, 9, 10].

The lighting criteria for pedestrian ways include illuminances of horizontal and vertical surfaces, and limitation of glare [6–10]. The lighting of horizontal surfaces is evaluated using the average horizontal illuminance ($E_{h,av}$), the minimum horizontal illuminance ($E_{h,min}$), the average hemispherical illuminance ($E_{hs,av}$), and the overall uniformity of the hemispherical illuminance (U_o). The lighting of vertical surfaces is evaluated using the minimum vertical illuminance ($E_{v,min}$) and the minimum semi-cylindrical illuminance ($E_{sc,min}$). The limitation of glare is evaluated using the threshold increment (*TI*), or the glare classes (*G*).

In applying the CIE 191 system for mesopic photometry, the values of mesopic luminances (L_{mes}) are calculated based on the photopic luminance and the light source S/P-ratio (ratio of scotopic-to-photopic luminous output). The S/P-ratio is defined by the spectral data of the light source. Mesopic lighting dimensions favour white light with a high S/P-ratio.

Light sources with a high colour rendering index also offer other benefits compared to the yellowish light of, for example, high pressure sodium (HPS) and low pressure sodium (LPS) lamps [11]. According to Raynham and Sakvirønning [11], white light makes people feel more comfortable doing outdoor activities at night. For example, people can more easily distinguish between objects, colours, shapes and other details under white light when walking, and they can detect movement along the roadside faster and from a farther distance under white light when driving [III].

Calculating mesopic luminance with the CIE 191 system for mesopic photometry requires the corresponding photopic luminance of the visual adaptation field. The visual adaptation field can be challenging to define due to the dynamic visual conditions that exist with night-time traffic. The different spatial density and spectral sensitivity of the rods and cones on the retina result in basic functional differences of the visual field [IV]. As a result, in 2012 the CIE established a Joint Technical Committee, JTC-1: 'Implementation of CIE 191 System for Mesopic Photometry in Outdoor Lighting'. The current task of the CIE JTC-1 is to investigate adaptation and viewing conditions and define visual adaptation fields for outdoor lighting [III].

1.2 Aim of the study

The first aim of this study is to review the current criteria for motor and pedestrian way lighting based on the CIE and CEN publications [5–10]. This review summarizes the studies behind the current road lighting recommendations and critically reviews them.

The second aim is to preliminarily investigate visual adaptation conditions and user preferences for pedestrian way lighting. By using an eye-tracking system, eye-fixation areas and locations are defined in order to study viewing and visual adaptation conditions. The eye-fixation areas and locations are expected to provide indicative knowledge on the visual adaptation field. By using a questionnaire survey, the relationships between lighting conditions and user preferences for a pedestrian way are studied, which is also useful to define the visual adaptation field.

2. State of the art

2.1 Mesopic photometric studies

Photometry is the measurement of quantities pertaining to radiation. The quantities are evaluated according to a given spectral luminous efficiency function, e.g. $V(\lambda)$ or $V'(\lambda)$ [1]. The functions $V(\lambda)$ and $V'(\lambda)$ were standardised as CIE standard spectral luminous efficiency functions for photopic and scotopic vision in 2004 [12]. At that time, the spectral luminous efficiency functions for mesopic vision were still under development. Two visual criteria, namely brightness matching and visual task performance, were proposed as the basis of the systems for mesopic photometry. With brightness matching, subjects match test stimuli to reference stimuli for equal brightness [13]. However, this method has been challenged because it could not meet the assumption of additivity provided by the CIE standard [14]. The rule of additivity states that the total luminance of a non-monochromatic light is the summation of the weighted spectral radiations of the component wavelengths measured linearly across the spectrum in order to quantify the corresponding luminous quantity [2]. With brightness matching experiments, when the test stimuli composed of several monochromatic components are compared to the reference stimuli, the combined effect is usually less than the sum of the luminances of the components [14]. Thus, brightness matching cannot obey the rule of additivity. Consequently, interest in the approach based on visual task performance for the mesopic photometric system began to increase towards the end of the 1990s.

Until the year 2010, several models were proposed as the basis for visual task performance-based mesopic photometry [4, 15, 16]. In 2010, the CIE published the Technical Report CIE 191:2010, *Recommended System for Mesopic Photometry Based on Visual Performance*. The recommended mesopic photometric system is valid between luminances of 0.005 cd/m^2 and 5 cd/m^2 [2].

In order to apply the CIE 191 system for mesopic photometry, both the photopic luminance of the visual adaptation field and the light source S/P-ratio are needed. The spectral characteristics of a light source are characterized by the S/P-ratio, which is defined as the ratio of the luminous output of the light source evaluated according to the CIE scotopic spectral luminous efficiency function, $V'(\lambda)$, to the luminous output evaluated according to the

CIE photopic spectral luminous efficiency function, $V(\lambda)$ [2]. Defining the visual adaptation field is the ongoing task of the CIE JTC-1.

2.2 Visual adaptation field

The CIE defines the field of vision (equivalent term: visual field) as the 'extent of space in which objects are visible to an eye in a given position. In the horizontal plane meridian the field of vision extends to nearly 190° with both eyes open, the area seen binocularly is about 120°, and the area seen by one eye only is about 154°' [1]. The society of Automotive Engineers (SAE), an organisation for engineering professionals in the aerospace, automotive, and commercial vehicle industries, has defined the field of view (visual field) as 'the extent of visual space over which vision is possible with the eyes in a fixed position (i.e., while looking straight ahead, it is the entire region of space visible)' [17].

In turn, adaptation is defined as the 'process by which the state of the visual system is modified by previous and present exposure to stimuli that may have various luminance values, spectral distributions and angular subtenses' [1]. The state of adaptation is the 'state of the visual system after an adaptation process has been completed' [1]. The visual adaptation field depends on the lighting conditions, and the behaviour of road users in various driving and walking conditions [III, IV].

In driving conditions, the useful field of view (UFOV) is a potential concept for defining the visual adaptation field. The UFOV is defined as 'the total visual field area in which useful information can be acquired without eye and head movements (within one eye-fixation)' [18]. The measures of UFOV include detecting an object, localising the object, and identifying the object against more complex visual backgrounds. As a result, the UFOV depends on the surroundings and on road users.

Various studies show that the UFOV depends on driving experience [19–22], and it is affected by the age of the driver as well as by the speed and duration of the driving task [23, 24]. Experienced drivers detect more peripheral targets than novice drivers [19, 22]. Novice drivers look more closely at the front of the vehicle and more to the right of the vehicle's direction than experienced drivers [20]. Novice drivers fixate on a particular object for a longer period of time than more experienced drivers, especially in dangerous situations [21]. In addition, the ability to detect peripheral targets decreases with increasing age [23]. The time needed to make decisions and shift one's attention while driving is affected by aging [24]. Drivers detect fewer targets in their peripheral visual field at high speeds; they also detect fewer signals in their central visual field when driving slowly [23].

In walking conditions, the visual tasks are different from those under driving conditions due to the different speed of movement and visual loads. Few studies on visual field under walking conditions have focused on real pedestrian environments. Most of the studies have been conducted indoors [25–29]. The eye-fixation of cyclists and pedestrians has been measured along different travel paths [30–32]. Itoh and Fukuda [28] referred that different estimations of the visual field in central and peripheral vision were based on the classification of retina in the book *The Retina*. Likewise, Polyak suggested that the central visual field extends from 0° to 16° and the peripheral visual field from 16° outwards in this book [33]. However, later studies have defined different central visual field sizes due to the different objectives of the experiments. For example, Brandt et al. [34] blocked the peripheral visual field and extended the central visual field up to 60° when studying the central/peripheral effect of vision on egocentric motion. Yoshida [35] considered the central visual field to only subtend 3° since this field accounts for more than 30% of visual acuity ability. In 1999, Bardy et al. considered the central visual field to subtend 30° when studying the roles of central and peripheral vision in postural control while walking [36]. In a study of oculomotor behaviour, Pelz defined a visual field as ranging from approximately ±20° horizontally to ±10° vertically because of the instrumental limitation of the experiment [30]. Generally, the peripheral visual field is dominant when it comes to controlling posture and keeping a proper stance under walking conditions [25]. Central and peripheral vision provide different information for walking; central vision is associated with orientation and peripheral vision with detection [29].

Under walking conditions, the visual field differs between young and elderly people [28, 30–32]. The central visual field of elderly walkers is wider than that of younger ones. The speed of eye movements is faster for elderly walkers than it is for younger walkers [28]. In addition, low-quality road surfaces cause users to concentrate more on the road area [30, 31]. Depending on the road and lighting conditions, users spend between 40% and 50% of their travel time observing the road surface [32].

One approach to studying the visual adaptation field is to conduct eye movement measurements under driving and walking conditions. This data can be combined with luminance information and pupil size measurements. This type of data is relevant for analysing central and peripheral vision in different outdoor lighting applications and for determining the actual adaptation conditions in different situations.

2.3 White light for pedestrian way lighting

For pedestrian way lighting, the EN 13201-2:2003 standard recommends the minimum maintained average horizontal illuminance for six lighting classes, ranging from 2.0 lx of S6 to 15.0 lx of S1. These values correspond to photopic luminances in the range of 0.04 cd/m^2 to 0.33 cd/m^2 with a given surface reflectance of 0.07 [37]. Thus, in pedestrian way lighting the visual system is operating in the mesopic range. The mesopic photometric system can be applied in pedestrian way lighting using different visual tasks for both central and peripheral vision, including the detection of obstacles, visual orientation, facial recognition, and safe movement [38].

The use of white light is gradually spreading to outdoor lighting [39]. Currently, white light has no official definition but it refers to light with a broad spectrum, a colour rendering index of R_a >60, and a S/P-ratio higher than 1.1 [37–39]. The appearance of a white light source is usually described by the correlated colour temperature (*CCT*). White light sources with a *CCT* that is higher than 5000 K have a cool colour appearance. A white light source with a *CCT* of around 2700 K has a warm colour appearance [38].

In pedestrian way lighting, white light offers benefits when compared with yellowish light. A British standard, BS5489-1:2003, discusses how to select a lighting class according to the traffic flow, environmental zone and prevailing crime rate [40]. It allows lower illuminances to be used for light sources with higher CRI ($R_a \geq 60$) compared to HPS lamps. This means that lighting classes can be reduced when using a light source with higher CRI ($\mathrm{R_a} \geq 60$) [37]. The average illuminance can be reduced for equal visual performance while using white light sources such as ceramic metal halide (CMH) lamps, compact fluorescent lamps (CFL), and white LEDs.

In addition, the light spectrum affects the visual perception and visual performance of pedestrians with respect to spatial brightness, colour recognition, facial recognition, and safe movement [38]. At mesopic light levels, the spectral sensitivity of the eyes shifts to short wavelengths; thus, white light with a relatively high output in the short wavelength region (high S/P-ratio) is favoured in mesopic photometry [III].

3. Review of lighting criteria for motor and pedestrian traffic

At present, the emphasis on traffic safety, the increasing concerns for energy efficiency and the development of mesopic photometry have led to increasing demands to consider the validity of the recommendations for road lighting. In Europe, the lighting requirements are quantified by the controlling criteria given in the CIE and CEN publications [5–10]. The lighting classes are generally selected and characterised on the basis of road classifications and the types of traffic. Lighting criteria for motor traffic are different from the criteria for pedestrian ways because of the different visual tasks involved. In China, the national standard CJJ 45-2006 [41] is applied for the lighting design of urban roads, including roads for vehicles and footways for pedestrians.

3.1 Review of lighting criteria for motor traffic

Lighting criteria for motor traffic are given in the CIE and CEN publications [5, 7, 9, 10]. The lighting criteria include road surface luminance and its distribution, the limitation of glare and lighting of surroundings of the road. Road surface luminance is evaluated using the average road surface luminance (L_{ave}), the overall uniformity of the luminance (U_o) and the longitudinal uniformity of the luminance (U_l). The limitation of glare, in particular disability glare, is evaluated using the threshold increment (*TI*). Lighting of surroundings of the road is evaluated using the surround ratio (*SR*) [5, 7, 9, 10].

The CIE 115:2010 report, *Lighting of Roads for Motor and Pedestrian Traffic* [10], is the updated version of the CIE 115:1995 report, *Recommendations for the Lighting of Roads for Motor and Pedestrian Traffic* [7]. The CEN publication EN 13201-2:2003 [9] is partly based on the CIE 115:1995 report [7]. The basis for the lighting criteria for motor traffic in CIE 115:1995 was taken from the CIE publication No. 12.2, *Recommendations for the Lighting of Roads for Motorized Traffic* [5]. As a result, the current lighting criteria for motor traffic are ultimately based on the CIE publication No. 12.2, which was published in 1977 [5].

3.1.1 Average road surface luminance

The basic requirement of lighting for motor traffic has to do with the average road surface luminance. As shown in Table 1, all of the publications recommend using a value of 2 cd/m² as the highest average luminance level. The road surface luminance is important for adequate visibility in matters pertaining to safety. Visibility was studied in laboratories or on real streets using both objective and subjective methods. Three fundamental experiments [42–44] were conducted to ascertain the suitable luminance level for adequate visibility in road situations. These studies recommend using a luminance level of 2 cd/m² for the average road surface luminance [5].

Table 1. The recommended minimum average road surface luminance (L_{ave}) based on the CIE and CEN publications [5, 7, 9, 10].

<table>
<tr><th colspan="2">CIE 12.2 :1977</th><th colspan="2">CIE 115:1995</th><th colspan="2">EN 13201-2:2003</th><th colspan="2">CIE 115:2010</th></tr>
<tr><td>Class</td><td>L_{ave} (cd/m^2)</td><td>Class</td><td>L_{ave} (cd/m^2)</td><td>Class</td><td>L_{ave} (cd/m^2)</td><td>Class</td><td>L_{ave} (cd/m^2)</td></tr>
<tr><td>A (any surrounds)</td><td>2.0</td><td>M1</td><td>2.0</td><td>ME1</td><td>2.0</td><td>M1</td><td>2.0</td></tr>
<tr><td>B1 (bright surrounds)</td><td>2.0</td><td rowspan="2">M2</td><td rowspan="2">1.5</td><td rowspan="2">ME2</td><td rowspan="2">1.5</td><td rowspan="2">M2</td><td rowspan="2">1.5</td></tr>
<tr><td>B2 (dark surrounds)</td><td>1.0</td></tr>
<tr><td>C1 (bright surrounds)</td><td>2.0</td><td rowspan="2">M3</td><td rowspan="2">1.0</td><td rowspan="2">ME3a, b, c</td><td rowspan="2">1.0</td><td rowspan="2">M3</td><td rowspan="2">1.0</td></tr>
<tr><td>C2 (dark surrounds)</td><td>1.0</td></tr>
<tr><td>D (bright surrounds)</td><td>2.0</td><td>M4</td><td>0.75</td><td>ME4a, b</td><td>0.75</td><td>M4</td><td>0.75</td></tr>
<tr><td>E1 (bright surrounds)</td><td>1.0</td><td rowspan="2">M5</td><td rowspan="2">0.5</td><td rowspan="2">ME5</td><td rowspan="2">0.5</td><td rowspan="2">M5</td><td rowspan="2">0.5</td></tr>
<tr><td>E2 (dark surrounds)</td><td>0.5</td></tr>
<tr><td></td><td></td><td></td><td></td><td>ME6</td><td>0.3</td><td>M6</td><td>0.3</td></tr>
</table>

Dunbar's studies in 1938

In 1938, Dunbar conducted an experiment in a real street lighting installation using a dynamic situation and established the standard critical contrast curve [42]. This curve illustrates the relationship between object contrast and road surface luminance. He defined the critical contrast as 'the difference between the brightness of the object and that of the background against which it is seen' [42]. By this definition, the brightness of the background is equal to the average road surface luminance, L_{ave}, the brightness of the object is the object luminance, L_o, and the contrast is expressed as $C= (L_{ave} - L_o)/ L_o$. For Dunbar's experiment, the road surface luminance was uniform and the observer was in a moving car travelling at a speed of 30 mph. (48 km/h). The experiment was conducted in a concrete carriageway (800 m long and 10 m wide), where the lamps (300 W each, but no description of the lamp types) were arranged in a triple suspension fashion with spacing of approximately 36 m and mounted at a height of 7.5 m. The tested object, a disc 0.45 m in diameter (reflectance of 0.6), was mounted at a height of 0.6 m above the road surface. To take effective action, 10 observers (no description of age) in a moving car were asked to describe which objects were at a position that was sufficient for safe driving. Each observer was expected to form his or her opinions before he or she was within 30 m of the object. During the testing process, the average road surface luminance (L_{ave}) changed from approximately 0.06 cd/m² to 2.05 cd/m². Only one object contrast was presented during each run, but the examiner altered the critical contrast in a bracketing method during successive runs until the required object position was discovered (a summary of the results is provided in Table 2).

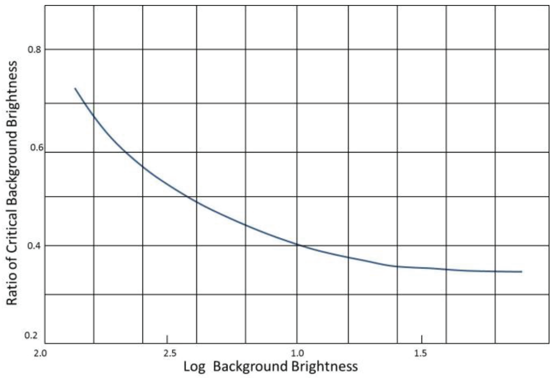


Figure 1. Relationship between L_{ave}/L_o and log L_{ave} [42].

As a result, Dunbar derived the standard critical contrast curve (Figure 1) and stated that when the background brightness, B, is equal to 1.0 equivalent foot-candles, the ratio, F (expressed as $(L_{ave} - L_o)/L_{ave}$), is equal to 1/3. Dunbar did not provide any detailed reason for choosing such a value for B [42]. With a contrast of 1/3, an L_{ave}/L_o ratio of 1.5 and a minimum average luminance (L_{ave}) of 2 cd/m^2 was needed for object detection [45]. Dunbar's study in 1938 was the first experiment to suggest a value of 2 cd/m^2 as the recommended minimum average road surface luminance for road lighting.

de Boer's studies in 1951

In 1951, de Boer conducted several fundamental experiments to judge the quality of road lighting in a static speed situation. For the experiments, lighting installations with 13 portals (10 m in height and 10 m in width) were hung 30 m apart from one another (Figure 2). The luminaires were positioned in the centre of each portal; the brightness of the road was then obtained based on these lighting installations. The length of the whole testing installation was 360 m, and the distance between the observers and the first luminaire was 30 m. All of the luminaires had incandescent lamps (no description of power). The quality of the road lighting was assessed in terms of road brightness and glare.

One approach to judging the quality of road lighting is to measure the contrast sensitivity of the observers. de Boer defined contrast sensitivity as 'background brightness divided by just perceivable brightness difference' [43]. The object chosen for the contrast sensitivity measurement was a 0.28 m × 0.28 m square containing 14 thin and narrow blades. These blades could turn around, but they were always supposed to remain parallel to one another. Different positions, such as open, half-closed and closed (Figure 3), were used for the blades. Eight observers with normal vision or vision corrected to normal participated in the experiments. The age of the observers varied between 20 and 39 years. Each observer viewed the blades at least four times in each condition (a summary of the results is provided in Table 2).

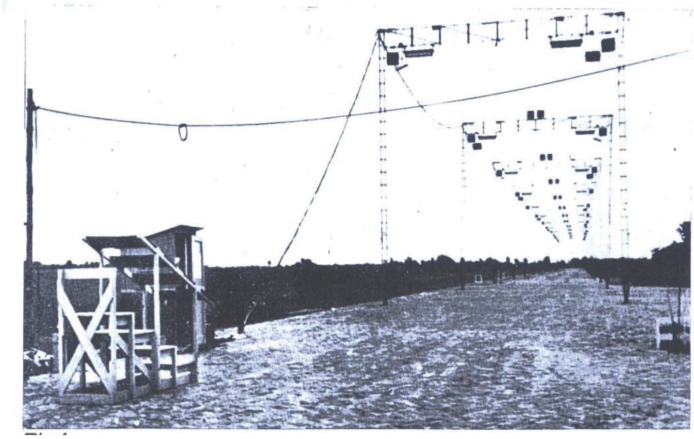
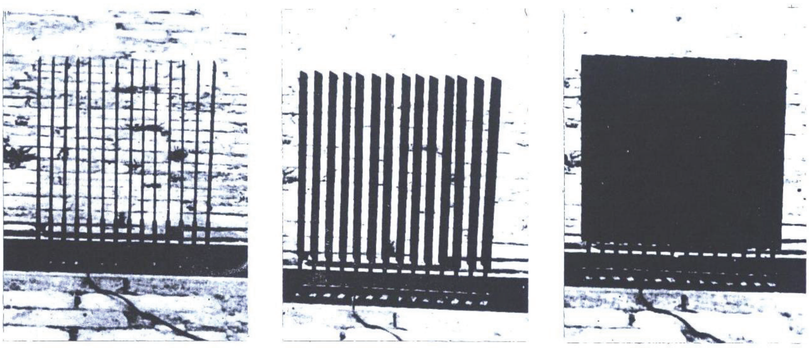


Figure 2. Experimental lighting installation [43].



a. b. c.

Figure 3. Devices for measuring contrast sensitivity: a. Contrast object (open); b. Contrast object (half-closed); c. Contrast object (closed) [43].

de Boer studied contrast sensitivity, visual acuity and visual speed as part of his experiment [43]. Similar results were achieved by Dunbar in 1938 (both with glare and without glare) (Figure 4). Both found that the contrast sensitivity curve changed slowly when the road luminance was between 0.2 cd/m² and 2 cd/m², and it remained stable when the value was approximately 2 cd/m². That is, the road surface luminance is adequate for visibility between luminances of 0.2 cd/m² and 2 cd/m² [43]. de Boer also concluded that 'if the glare is kept within limits set by comfort requirements; good visibility is assured if road brightness is sufficiently high' [43]. Dunbar suggested continuing the work under conditions more similar to those that would be encountered in practice. Based on the studies, de Boer et al. continued their experiments in different situations with the aim of providing recommendations for adequate light levels.

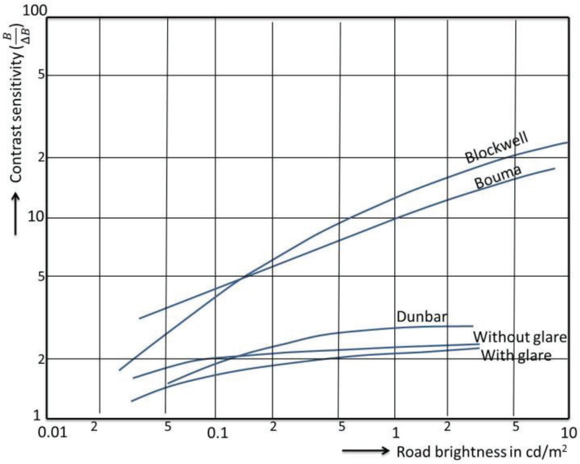


Figure 4. The contrast sensitivity curves [43].

Studies by de Boer et al. in 1959

In 1959, de Boer et al. conducted three series of experiments and made recommendations for road lighting [44]. The first experiment had to do with making a subjective appraisal of the luminance level in road lighting. They appraised seventy existing street lighting installations: 46 on dry road surfaces and 24 on wet road surfaces. Two groups of observers, consisting respectively of 6 and 10 people, participated in the experiment. The light sources were sodium, incandescent, fluorescent, and colour-corrected high pressure mercury lamps (no description of power). The second experiment was conducted to find out the effects of colour on the visual appraisal of luminance levels. Static visibility distances on dry road surfaces were determined using Landolt rings with a diameter of 0.16 m and a reflection factor of 9% as the test objects. Twenty-five existing installations and an outdoor laboratory set-up were appraised by four observers. The ages of the observers in the first two experiments ranged from 22 to 40 years. The light sources were sodium and colour-corrected mercury lamps. The final experiment consisted of a dynamic visibility test, which was conducted using a moving car at a speed of 50 km/h. The subjects estimated the distance at which a 20 cm × 20 cm mat screen could be seen. Four observers, aged 24, 29, 20 and 40 years, participated in the experiment (a summary of the results is provided in Table 2).

The above experiments [44] were conducted under dynamic conditions and using similar lighting installation as the studies done in 1951. In their 1959 study, de Boer et al. again proposed using a value of 2 cd/m^2 as the required minimum average luminance for the road surface. The visual evaluations were conducted both in the actual installations and in an outdoor laboratory. The observers were sitting in cars. They gave their opinions (excellent, good, fair, inadequate or bad) on the luminance level, the luminance pattern and the degree of glare after looking at each installation from the driving track. The actual installation test consisted of a group of six people. In the outdoor laboratory, luminaires with sodium, incandescent, fluorescent and colour-corrected high pressure mercury lamps were tested by a second group of ten people.

The results, shown in Figure 5, illustrate the relationship between the evaluation of the luminance level ($VE_{\bar{B}}$) and the average luminance ($\bar{B}$). The average luminance ($\bar{B}$) is equal to the road surface luminance. When the observers subjectively judged the luminance level as being 'good', the luminance of the road surface had a mean value of 1.5 cd/m². As stated in their study: 'It may be observed that the value of 2 cd/m², recommended for the average luminance of the road surface for busy traffic in the 'Nederlandse Aanbevelingen voor Weg-en Straatverlichting' (Netherlands Recommendations on Public Lighting), comes close to the value found here' [44]. Thus, de Boer et al. recommended a value of 2 cd/m² as the average road surface luminance, which they tested in an outdoor laboratory during the experiments. In addition, they concluded that the colour of the light had an influence on visibility. Sodium lamp lighting provided more favourable results in terms of visibility distance than colour-corrected mercury lamps when the road surface had the same luminance level [44].

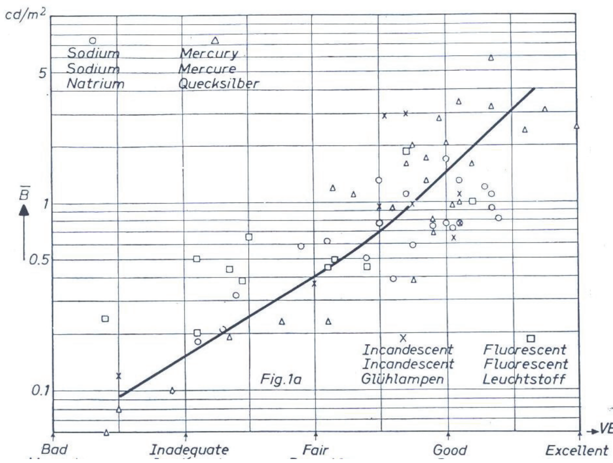


Figure 5. Appraisal of luminance level [44].

Table 2. Summary of the experiments [42–44].

Experiments	Experimental set-up					Vision	Restrictions	Results
	No. of observers	Age	Light sources	Road	Speed			
Dunbar, 1938	11	Not stated	Lamp type not given, 300 W each	Length 800 m (straight), width 9.1 m, concrete surface	48.3 km/h	foveal	Valid only for dry road surfaces and when there is no glare from the street lamps.	Recommended average road surface luminance range: 0.6 – 2.05 cd/m^2
de Boer, 1951	8	20 –39, average 26	Incandescent lamp, 5 W - 300 W	Not stated	static	foveal	Experimental conditions are not much like those encountered in practice.	If glare is kept within the limits set by comfort requirements and road brightness is sufficiently high, good visibility is assured.
de Boer et. al, 1959								
Subjective appraisal of luminance	16	22 – 40, average 27	Sodium, incandescent, fluorescent and colour-corrected high pressure mercury lamps	70 existing street lighting installations: 46 dry and 24 wet road surfaces	static	Not stated	The influence of glare on the appraisal was not taken into account.	Luminance level appraised as ‘good’ when the luminance of the road surface had a mean value of 1.5 cd/m^2.
Effects of colour on light level	4	22 – 40, average 27	Sodium and colour-corrected mercury lamps	25 existing installations and outdoor laboratory	static	foveal	Not stated	Colour had an influence on the visual appraisal of the luminance level.
Dynamic visibility test	4	24, 29, 30, 40	Sodium and colour-corrected mercury lamps	25 existing installations described above	50 km/h	foveal	Not stated	A 20 cm × 20 cm object, of which the luminance was 2/3 that of the background, must be visible at least 100 m away.

3.1.2 The uniformity of road surface luminance

The uniformity of road surface luminance is one factor affecting visibility and the visual comfort of road users [45]. Earlier proposals for how to define uniformity were discussed in CIE 31:1976 report [46]. It was stated that '*CIE publication No. 12 (1965) gave a recommendation about L_{min}/L_{ave} for 'good' uniformity*' [46]. However, the CIE publication No. 12 was later withdrawn and replaced by the CIE publication No. 12.2, published in 1977 [5]. The CIE publication No. 12.2 recommended that the overall uniformity of luminance have a minimum ratio of L_{min}/L_{ave} in order to provide sufficient visibility, and that the longitudinal uniformity of luminance should be defined as the ratio of L_{min}/L_{max} along the centre line of each lane on the road in order to provide visual comfort. In addition, the relationship between road surface luminance and uniformity has been stated as follows: 'as the luminance increase, the requirement for uniformity is less stringent' [5]. Furthermore, '...in public lighting installations, the average road surface luminance (L_{ave}) should be determined in connection with the uniformity (U). Effective lighting conditions could be attained even with relatively low average road surface luminance, as long as a high uniformity (U) can be maintained' [47]. Moreover, the uniformity of road surface luminance also affects the cost of lighting installations. The CIE 31:1976 report states that:

'The uniformity has to be good enough to satisfy the two (the visual performance and the visual comfort) first demands without being too costly. It is necessary to try to find a reasonable compromise between the need for good visibility and visual comfort-factors which are important for traffic safety and the economic realities'.

In conclusion, not only the visual perception, but also economic and cost-benefit reasons need to be considered when making luminance uniformity recommendations. Beyond these factors, the uniformity of road surface luminance is also affected by weather. Uniformity can be quite poor on a wet road surface while it can be good in dry weather [5].

In previous studies, such as the one used by the CIE in 1976 [46], the average road surface luminance (L_{ave}), maximum road surface luminance (L_{max}) and minimum road surface luminance (L_{min}) have been considered necessary parameters for determining uniformity and for defining the overall uniformity ($U_o = L_{min}/L_{ave}$), and the longitudinal uniformity ($U_l = L_{min}/L_{max}$) along the longitudinal line on the road surface and the transverse uniformity (L_{min}/L_{max}) along the transverse line on the road surface [46]. Although the transverse uniformity is important for visibility, investigations by both De Grijs (1971) [48] and Frederiksen (1972) [49] referred to the CIE publication of 1976 [46] and proved that it has no influence on the appraisal of uniformity. As a result, the overall uniformity and the longitudinal uniformity of luminance are the two factors that now determine the uniformity of road surface luminance in the recommendations.

The overall uniformity of luminance

The overall uniformity of luminance (U_o) is the ratio of the minimum road surface luminance to the average road surface luminance [5]. As shown in Table 3, all publications [5, 7, 9, 10] recommend using a value of 0.4 for the overall uniformity of luminance for dry road surfaces. The overall uniformity of luminance is related to the visual performance of the road users.

Table 3. The recommended overall uniformity of luminance (U_o) based on the CIE and CEN publications [5, 7, 9, 10].

CIE 12.2 : 1977		**CIE 115:1995**		**EN 13201-2:2003**		**CIE 115:2010**	
Class	U_o	Class	U_o	Class	U_o	Class	U_o
A (any surrounds)	0.4	M1	0.4	ME1	0.4	M1	0.4
B1 (bright surrounds)	0.4	M2	0.4	ME2	0.4	M2	0.4
B2 (dark surrounds)							
C1 (bright surrounds)	0.4	M3	0.4	ME3a, b, c	0.4	M3	0.4
C2 (dark surrounds)							
D (bright surrounds)	0.4	M4	0.4	ME4a, b	0.4	M4	0.4
E1 (bright surrounds)	0.4	M5	0.4	ME5	0.35	M5	0.35
E2 (dark surrounds)							
				ME6	0.35	ME6	0.35

The basis for using overall uniformity values of 0.4 was provided by Schreuder's 1964 tunnel entrance experiment, which was summarized by De Grijs in 1971 [48]. De Grijs stated that,

'Mean road surface luminance $\bar{L}$ is taken as adaptation luminance and the minimum luminance (L_{min}) is the immediate background against which an object of 8′ (minutes of arc) and 20% luminance difference should be seen. A minimum value of $L_{min}/\bar{L}$=0.4 is found to be necessary in the range for $\bar{L}$ from 1 to 3 cd/m², in order for the object to be perceptible in 75% of the case within 0.1 sec'.

The mean road surface luminance ($\bar{L}$) mentioned here is the same as the average road surface luminance (L_{ave}). The recommendations for the overall uniformity of luminance in the lighting classes with an average road surface luminance of less than 1 cd/m² supposedly lack experimental support.

Longitudinal uniformity of luminance

The longitudinal uniformity of luminance (U_l) is the ratio of the minimum road surface luminance to the maximum road surface luminance along the centre line of each lane on the road [5]. As shown in Table 4, all of the publications [5, 7, 9, 10] recommend using a value of 0.7 as the highest longitudinal luminance uniformity value. It is stated that this shall 'prevent the repeated pattern of high and low luminance values on a lit run of road' [10].

Though no specific study was conducted to derive the values of longitudinal uniformity of luminance, De Grijs (1971) [48] and Walthert (1973) [50] collected quantitative information related to longitudinal uniformity of luminance.

Table 4. The recommended longitudinal uniformity of luminance (U_l) based on the CIE and CEN publications [5, 7, 9, 10].

CIE 12.2: 1977		**CIE 115:1995**		**EN 13201-2:2003**		**CIE 115:2010**	
Class	U_l	Class	U_l	Class	U_l	Class	U_l
A (any surrounds)	0.7	M1	0.7	ME1	0.7	M1	0.7
B1 (bright surrounds)	0.7	M2	0.7	ME2	0.7	M2	0.7
B2 (dark surrounds)							
C1 (bright surrounds)	0.5	M3	0.5	ME3a	0.7	M3	0.6
C2 (dark surrounds)				ME3b	0.6		
				ME3c	0.5		
D (bright surrounds)	0.5	M4	*NR	ME4a	0.6	M4	0.6
				ME4b	0.5		
E1 (bright surrounds)	0.5	M5	*NR	ME5	0.4	M5	0.4
E2 (dark surrounds)							
				ME6	0.4	M6	0.4

*NR= No recommendation.

3.1.3 Threshold increment

Threshold increment (*TI*) is the measure of disability glare. Disability glare results from the scattering of light within the eye; this causes loss of visibility and a reduction in retinal contrast[10]. TI is a measure of disability glare expressed as the percentage increase in contrast required between an object and its background for it to be seen equally well with a source of glare present [1]. The *TI* is quantified by the equivalent veiling luminance, and the method of evaluation is based on the Holladay formula [5]. As shown in Table 5, CIE publication No. 12.2 [5] recommended a value of 20% as the highest allowable threshold increment. Other publications [7, 9, 10] recommend a value of 15% as the highest allowable threshold increment.

Both disability glare and discomfort glare affect visual performance. However, no completely satisfactory method has been developed so far to quantify the discomfort glare experienced by road users. The CIE 31-1976 report [46] discusses glare classes (G) for evaluating discomfort glare; the CIE publication No. 12.2 also recommends using these glare classes (G), but they can result in anomalies. The glare classes (G) have difficulties to be determined for curved road sections, but are applicable to straight road with evenly spaced luminaires [46]. As a result, both CIE and CEN publications [5, 7, 9, 10] suggest that road lighting installations should be designed using the criteria for *TI*.

Table 5. The recommended threshold increment (*TI* (%)) based on the CIE and CEN publications [5, 7, 9, 10].

CIE 12.2: 1977		**CIE 115:1995**		**EN 13201-2:2003**		**CIE 115:2010**	
Class	*TI* (%)	Class	*TI* (%)	Class	*TI* (%)	Class	*TI* (%)
A (any surrounds)	10	M1	10	ME1	10	M1	10
B1 (bright surrounds) B2 (dark surrounds)	10	M2	10	ME2	10	M2	10
C1 (bright surrounds)	20	M3	10	ME3a	15	M3	15
				ME3b	15		
C2 (dark surrounds)	10			ME3c	15		
D (bright surrounds)	20	M4	15	ME4a	15	M4	15
				ME4b	15		
E1 (bright surrounds) E2 (dark surrounds)	20	M5	15	ME5	15	M5	15
				ME6	15	M6	20

3.1.4 Surround ratio

Surround ratio (*SR*) is defined as the ratio of the average horizontal illuminance on the two longitudinal strips adjacent to the road edges but lying just off the road to the average horizontal illuminance on the longitudinal strip adjacent to the road edges but lying just on the road [10]. The width of each longitudinal strip is usually 5 m, or half the width of the carriageway; dual carriageways that are no more than 10 m in width are also treated as a single carriageway. The surround ratio ensures that a sufficient amount of light falls on the surrounds of the road. As shown in Table 6, several publications [8, 10, 11] recommend using a minimum value of 0.5 as the surround ratio, but CIE publication No. 12.2 [5] makes no recommendations for *SR*.

Table 6. The recommended surround ratio (*SR*) based on the CIE and CEN publications [8, 10, 11].

CIE 115:1995		**EN 13201-2:2003**		**CIE 115:2010**	
Class	*SR*	Class	*SR*	Class	*SR*
M1	0.5	ME1	0.5	M1	0.5
M2	0.5	ME2	0.5	M2	0.5
M3	0.5	ME3a	0.5	M3	0.5
		ME3b	0.5		
		ME3c	0.5		
M4	NR	ME4a	0.5	M4	*NR
		ME4b	0.5		
M5	NR	ME5	0.5	M5	*NR
		ME6	*NR		

*NR= No recommendation.

Sufficient illumination of the road surrounds helps motorists perceive the environment better and adjust their speed in time. The significance of *SR* has to do with ensuring a sufficient amount of light for areas surrounding either side of the road so that all objects can be observed [10].

While the CIE publication No. 12.2 does not recommend a value for *SR*, it discusses the surround lighting: 'An analysis of lighting installations of good quality shows that for most road situations and for most types of light distributions employed, a stretch of some 5m in width beyond carriageway is illuminated to a level not less than 50% of that of the adjacent 5 meters of carriageway. This situation is desirable as a safeguard against inadequate lighting of the surrounds' [5]. The publication discusses the lighting of surrounds of road without providing any references; nonetheless, its recommendations became part of the controlling criteria for the quality of road lighting later in CIE 115: 1995 report [7]. The reports CIE 115: 1995, EN 13201-2:2003 and CIE 115:2010 all recommend *SR* as a criterion for the lighting of the road surrounds; this recommendation is valid for roads with footways where there is no separate pedestrian way lighting.

3.2 Review of lighting criteria for pedestrian ways

Pedestrian way lighting is different from motor traffic lighting because of the different visual tasks faced by pedestrians and drivers. The visual tasks faced by pedestrians include safe movement, visual orientation and facial recognition. Feeling secure is also relevant [38]. The key criterion for safe movement has to do with detecting obstacles or other hazards, while feeling secure has to do with observing one's surroundings, including identifying other pedestrians and possible criminal activities [38].

Pedestrian way lighting criteria are given to provide a sufficient light level (illuminance), uniformity (illuminance uniformity), and limitation of glare [7–11]. Uniformity is evaluated using the ratio of the maximum to the minimum illuminance. Uniformity is discussed in several previous studies [9]. Light level is evaluated using the average horizontal illuminance ($E_{h,av}$), the minimum horizontal illuminance ($E_{h,min}$), the average hemispherical illuminance ($E_{hs,av}$), the minimum vertical illuminance ($E_{v,min}$) and the minimum semi-cylindrical illuminance ($E_{sc,min}$). Glare is evaluated using the *TI*, the glare classes (*G*), or the luminaire glare restriction formula [6–10].

The lighting classes are generally selected and characterised by several parameters, such as the traffic volume and environmental conditions. The limitation of glare is not as critical for pedestrians as it is for motorists because of their lower speed of movement and because they have more time to react. There are no internationally agreed upon standards for recommending the glare limitation, but a number of national methods are currently in use [51]. Lighting criteria for the limitation of glare are mostly presented as an appendix in the above publications. As a result, the light level (illuminance) is the only lighting criterion discussed in the following publications.

CIE 92:1992 report, *Guide to the Lighting of Urban Areas* [6], provides recommendations for lighting of public thoroughfares, including cycle tracks, pedestrian areas and malls, residential and other non-arterial routes, alleys and lanes. The light levels for pedestrian ways are given in terms of horizontal illuminance ($E_{h,ave}$ and $E_{h,min}$) and semi-cylindrical illuminance ($E_{sc,min}$). Lighting classes are selected based on the environment and types of footways, with the environment being classified as a city or town centre, suburban shopping streets, and village centres. Street types contain mixed vehicle and pedestrian ways as well as ways that are only used by pedestrians.

CIE 115:1995 report, *Recommendations for the Lighting of Road for Motor and Pedestrian Traffic* [7], provides recommendations only for horizontal illuminances ($E_{h,ave}$ and $E_{h,min}$); though the publication discusses semi-cylindrical illuminance, it does not make any recommendations. In addition, CIE 115:1995 report provides a list of seven lighting classes, P1 to P7, the selections of which are based on the traffic volume, types of footways and environmental conditions.

CIE 136:2000 report, *Guide to the Lighting of Urban Areas* [8], which replaced the CIE 92:1992 report and served as a supplement to the CIE 115:1995 report, discusses the lighting criteria for public thoroughfares. Light levels for urban traffic, including pedestrian ways, are defined based on seven classes; these classes are the same as those mentioned in the CIE 115:1995 report. In addition, it makes recommendations regarding semi-cylindrical illuminance ($E_{sc,min}$) based on those in the CIE 92:1992 report.

EN 13201-2:2003 report, *Road Lighting. Part 2: Performance Requirements* [9], recommends illuminance levels for pedestrian ways based on a series of lighting classes. The lighting classes are defined according to S, A, ES and EV series, which are based on the category of road users or the footway types. S classes use horizontal illuminance, including the minimum maintained values of $E_{h,ave}$ and $E_{h,min}$, whereas A classes use hemispherical illuminance, including the average minimum maintained values for $E_{hs,ave}$ and U_o (hemispherical illuminance uniformity). Both the S and A classes provide lighting criteria for pedestrians and cyclists for different pathway types. ES classes provide the criteria for $E_{sc,min}$ in order to reduce crime and increase the feeling of safety. EV classes use the criteria for average vertical illuminance ($E_{v,min}$) when observing vertical surfaces.

CIE 115:2010 report, *Lighting of Roads for Motor and Pedestrian Traffic* [10], discusses good quality lighting for residential streets and provides lighting criteria for pedestrians based partly on the CIE 136:2000 report. The lighting criteria include $E_{h,ave}$ and $E_{h,min}$. Additionally, $E_{v,min}$ and $E_{sc,min}$ are recommended for facial recognition.

3.2.1 Lighting of horizontal surfaces

Along footways for pedestrians, the lighting of horizontal surfaces is evaluated using both the average ($E_{h,av}$) and the minimum ($E_{h,min}$) values of the horizontal illuminances. The main purpose is to ensure the safe movement of pedestrians [10]. As shown in Table 7, the recommended $E_{h,av}$ in the lighting classes ranges from 1.5 lx to 25 lx depending on the environment and types of footways [6–10]. The minimum value ($E_{h,min}$) was given as 0.2 lx in the 1990s [7], but it has since been updated to 0.4 lx or 0.6 lx in later publications, such as EN 13201-2:2003 and CIE 115:2010.

In CIE 92:1992 report [6], the values for $E_{h,av}$ range from 8 lx to 25 lx and the values for $E_{h,min}$ range from 2 lx to 10 lx, depending on the environment (city or town centres, suburban shopping streets, or village centres) and types of pathways (mixed vehicle and pedestrian, or solely pedestrian). However, this publication has been replaced by the CIE 136:2000 report [8], in which both the lighting classes and light levels are updated.

The CIE 115:1995 report recommends horizontal illuminance using seven lighting classes (P1 to P7) for pedestrian ways. These same recommendations were also given in the CIE 136:2000 report, which used the same lighting classes and light levels. The EN 13201-2:2003 report recommends lighting classes ranging from S1 to S7. The P and S classes have similar values for $E_{h,av}$ (Table 7), except that the S1 class has a lower value of 15 lx in the EN 13201-2:2003 report than the P1 class (20 lx) in the CIE 136: 2000 report, whereas the P6 class has a lower value of 1.5 lx in the CIE 136:2000 report than the S6 class (2 lx) in the EN 13201-2:2003 report. The values for $E_{h,min}$ were updated with smaller range of between 3 lx and 0.4 lx for the P1 to P6 classes in the CIE 115:2010 report. In the EN 13201-2:2003 report, the values for $E_{h,min}$ range between 5 lx and 0.6 lx for the S1 to S6 classes. In contrast, the values for $E_{h,min}$ range between 3 lx and 0.4 lx for the P1 to P6 classes in the CIE 115: 2010 report (see Table 7).

Table 7. The recommended average horizontal illuminance ($E_{h,\ av}$) and minimum horizontal illuminance ($E_{h,\ min}$) based on the CIE and CEN publications [6–10].

CIE 92: 1992				CIE 115: 1995			CIE 136: 2000			EN 13201-2:2003			CIE 115: 2010		
Class		$E_{h,av}$ (lx)	$E_{h,min}$ (lx)	Class	$E_{h,av}$ (lx)	$E_{h,min}$ (lx)	Class	$E_{h,av}$ (lx)	$E_{h,min}$ (lx)	Class	$E_{h,av}$ (lx)	$E_{h,min}$ (lx)	Class	$E_{h,av}$ (lx)	$E_{h,min}$ (lx)
City or Town Centres	*Mixed	25	10	P1	20	7.5	P1	20	7.5	S1	15	5	P1	15	3.0
	**Ped.	15	5	P2	10	3	P2	10	3	S2	10	3	P2	10	2.0
Suburban Shopping Streets	Mixed	20	8	P3	7.5	1.5	P3	7.5	1.5	S3	7.5	1.5	P3	7.5	1.5
	Ped.	10	3	P4	5	1	P4	5	1	S4	5	1	P4	5.0	1.0
Village Centres	Mixed	10	4	P5	3	0.6	P5	3	0.6	S5	3	0.6	P5	3.0	0.6
	Ped.	8	2	P6	1.5	0.2	P6	1.5	0.2	S6	2	0.6	P6	2.0	0.4
				P7	Not applicable		P7	Not applicable		S7	Performance not determined				

*Mixed: mixed vehicle and pedestrian.
**Ped.: solely pedestrian.

The recommended illuminance levels shown in Table 7 are based on studies conducted during the 1970s and 1980s [52–63]. These studies discussed values for average horizontal illuminance ranging from 1 lx to 20 lx depending on the purpose of the public lighting in residential areas. Minimum horizontal illuminance can be deduced based on the studies of emergency lighting [51, 64–67].

Previous studies recommended using a value of 5 lx for $E_{h,av}$ to provide a basis for visibility along the road [53–59, 62]. Studies also recommend using this value as the general average horizontal illuminance for pedestrian areas [60] and for facilitating a positive orientation [61]. In 1978, Tan[52] investigated the required light level for residential streets. He found that a value of 2 to 3 lx should be accepted by the lighting experts, residents and police authorities. Residents accepted a lower value of 1 to 2 lx , but lighting experts and police authorities objected this value was too low [52]. A higher value for the average horizontal illuminance, such as 15 lx, was recommended in a German guide to arcades and passageways [61]. Likewise, a value of 20 lx was mentioned for recognising human features [63]. All of these values are summarised in Table 8.

The minimum horizontal illuminance for pedestrian way lighting can be deduced based on studies of emergency lighting [51]. In one such study [51], van Bommel discussed using a minimum horizontal illuminance of 1 lx, which was recommended in the CIE draft document *Guide on the Emergency Lighting of Premises* in 1979. This document was unpublished, but it was replaced by the CIE 49:1981 report *Guide on the Emergency Lighting of Building Interiors* [65]. The CIE 41:1989 report recommends that the horizontal illuminance for escape routes should be no less than 0.2 lx in order to detect obstacles. A higher value of 1 lx is preferred for moving rapidly and confidently while making an escape. The BSI (British Standard Institute) in BSI 5266-1 [66] and NNI (Nederland Normalisatie Instituut) NEN1010 [68] standards recommend using a value of 1 lx for the minimum illuminance with respect to emergency lighting. In 1975, Simmons [64] recommended using a value of 0.2 lx for emergency lighting. He suggested using a value of 0.28 lx as a safe minimum illuminance based on how the subjects performed during the experiments. However, a value of 0.2 lx would be the lowest one used in practice [64].

Table 8. The recommended average horizontal illuminances in [52–61, 63].

Illuminance	References	Remarks
1 to 2 lx	Tan, 1978[52].	Accepted by residents, but lighting experts and police authorities disagreed with this value, arguing that it was too low.
2 to 3 lx	Tan, 1978[52].	Accepted by residents, lighting experts and police authorities
5 lx	NSVV, 1974/1975[53]–[55]; NSVV, 1977[56]; Hendriks, 1978[57]; Schreuder, 1978[58]; Schreuder, 1979[59].	Basis for visibility along pedestrian way
	de Boer, 1975[60].	General average horizontal illuminance for pedestrian areas
	FGS, 1977[61].	Facilitating a positive orientation
15 lx	FGS, 1977[61].	Recommended for arcades, passageways
20 lx	Fischer, 1973[63].	Recognition of human features

3.2.2 Lighting of vertical surfaces

With respect to the current recommendations for pedestrian way lighting, the purpose of lighting of vertical surfaces is to detect vertical surfaces and to enable facial recognition. The recommendations pertain to the vertical illuminance, hemispherical illuminance and semi-cylindrical illuminance. Vertical illuminance is the illuminance on the vertical plane [1]. Semi-cylindrical illuminance is the arithmetic mean of the vertical illuminance, which is at a point in the range of azimuth angles [1]. Hemispherical illuminance is luminous flux on a small hemisphere with a horizontal base, divided by the surface area of the hemisphere [9]. The use of hemispherical illuminance, shown in Table 9, is rare. The only recommendations for it are given in the EN13201-1:2003 report; they derive from the values for minimum hemispherical illuminance ($E_{hs,min}$) and the overall uniformity of hemispherical illuminance (U_o). The values for $E_{hs,min}$ derive from the Danish recommendation for various categories of residential roads, with the values ranging from 1 lx to 5 lx [69].

Table 9. The recommended minimum hemispherical illuminance ($E_{hs,min}$) and overall uniformity of hemispherical illuminance (U_o) based on the CEN publication [9].

Class	**$E_{hs,min}$ (lx)**	**U_o (minimum)**
A1	5	0.15
A2	3	0.15
A3	2	0.15
A4	1.5	0.15
A5	1	0.15
A6	Performance not determined	Performance not determined

In general, the lighting of vertical surfaces is characterised by the average vertical illuminance ($E_{v,av}$) and the minimum semi-cylindrical illuminance ($E_{sc,min}$). Only the EN 13201-2:2003 report and the CIE 115:2010 report make recommendations regarding the vertical illuminance. As shown in Table 10, the values suggested in the different publications differ greatly. The values for $E_{v,av}$ range from 50 lx to 0.5 lx in the EN 13201-2:2003 report, but they range only from 5.0 lx to 0.6 lx in the CIE 115:2010 report. The difference can be explained by the different tasks; the recommendation provided in the EN 13201-2:2003 report is for situations involving interchange areas where vertical surfaces need to be observed, while the recommendation provided in the CIE 115:2010 report is based on the needs of facial recognition.

Table 10. The recommended average vertical illuminance ($E_{v,av}$) based on the CEN and CIE publications [9], [10].

EN 13201-2:2003		**CIE 115: 2010**	
Class	$E_{v,av}$ (lx)	Class	$E_{v,av}$ (lx)
EV1	50	P1	5.0
EV2	30	P2	3.0
EV3	10	P3	2.5
EV4	7.5	P4	1.5
EV5	5	P5	1.0
EV6	0.5	P6	0.6

The studies rarely deduced directly the values for vertical illuminance. In subjective assessments of residential road lighting, vertical illuminance is essential for providing a sense of visual orientation in which the features of the environment, such as buildings and plants, need to be identified [70]. Reviewing the studies conducted in the 1970s, Schreuder in his study on lighting for residential yards suggested that the value for vertical illuminance should be 20 lx when it is important to observe human facial expressions [71]. He arrived at this value based on Fischer's studies of the lighting levels needed in order to identify human features in working interiors [63, 72]. Fischer recommended using four illuminance levels to identify facial features and viewing conditions (Table 11). He suggested that a value of 20 lx is the minimum vertical illuminance in which facial features can be barely discerned. However, later studies in the 1980s concentrated on facial recognition based on semi-cylindrical illuminance [62, 73, 74].

Table 11. Four illuminance levels for identifying facial features and viewing conditions [63, 72].

Illuminance (lx)	Signification	Conclusions
20	Features of human face just discernible	Minimum illuminance for public places and corridors should be 20 lx
200	Features of human face just acceptably perceptible	Minimum illuminance for working interiors should be 200 lx
2 000	Optimum viewing conditions in normal working interiors	A range of between 200 and 2 000 lx is suggested for general lighting in normal working interiors
20 000	Task luminance of at least 1 000 cd/m2 for a reflectance above 0.15	A range of between 2 000 and 20 000 lx is suggested for local lighting for visually exacting tasks

The semi-cylindrical illuminance ($E_{sc,min}$) recommended in publications CIE 92:1992, CIE 136:2000, EN13201-1:2003 and CIE 115:2010 has different values depending on the lighting class. While the CIE 115:1995 report discussed semi-cylindrical illuminance, it did not make any recommendations regarding it. As shown in Table 12, the CIE 92:1992 report recommended using values ranging from 10 lx to 3 lx for $E_{sc,min}$. However, this report was replaced by the CIE 136:2000 report, which redefined the lighting classes using seven different classes (P1 to P7) with values for $E_{sc,min}$ ranging from 5 lx to 0.5 lx. The EN 13201-2:2003 report uses nine lighting classes (ES1to ES9) for $E_{sc,min}$ ranging from 10 lx to 0.5 lx. However, the CIE 115:2010 report [10] narrows the range for $E_{sc,min}$ from 3 lx to 0.4 lx for the six lighting classes P1 to P6.

Table 12. The recommended minimum semi-cylindrical illuminance ($E_{sc,min}$) for pedestrian way lighting based on the CIE and CEN publications [6, 8–10].

CIE 92: 1992			CIE 136: 2000		EN 13201-2: 2003		CIE 115: 2010	
Class		$E_{sc,min}$ (lx)	Class	$E_{sc,min}$ (lx)	Class	$E_{sc,min}$ (lx)	Class	$E_{sc,min}$ (lx)
City or Town Centres	*Mixed	10	P1	5	ES1	10	P1	3.0
	**Ped.	5	P2	2	ES2	7.5	P2	2.0
Suburban Shopping Streets	Mixed	8	P3	1.5	ES3	5	P3	1.5
	Ped.	4	P4	1	ES4	3	P4	1.0
Village Centres	Mixed	4	P5	0.75	ES5	2	P5	0.6
	Ped.	3	P6	0.5	ES6	1.5	P6	0.4
			P7	Not applicable	ES7	1		
					ES8	0.75		
					ES9	0.5		

*Mixed: mixed vehicle and pedestrian.
**Ped.: solely pedestrian.

The basis for the semi-cylindrical illuminance recommendations lies in research done by Caminada and Van Bommel [62, 73, 74]. They used an observation distance of 4 m, which was based on studies by Hall on human behaviour at different distances [75]. Caminada and Van Bommel concluded that the semi-cylindrical illuminance necessary for facial recognition is 0.8 lx at a distance of 4 m and 2.7 lx at the distance of 10 m. However, a later study by Rombauts et al. found that facial recognition can be achieved at a minimum semi-cylindrical illuminance of 0.6 lx at a distance of 4 m [76].

3.2.3 Lighting criteria for pedestrian ways in China

Road lighting design in China is based on national standards. The Ministry of Construction (MOC) in China published CJJ 45-2006, *Standard for Lighting Design of Urban Road*, in 2006; it was prepared by the China Academy of Building Research (CABR) and replaced CJJ 45-91, *Standard for Lighting Design of Urban Road* [41]. Lighting criteria for pedestrian ways provide sufficient illuminance levels for $E_{h,av}$, $E_{h,min}$ and $E_{v,min}$. The lighting classes are selected and characterised based on the volume of pedestrians (heavy, medium and light) and the environmental conditions (commercial area or residential area). Depending on the different areas, all of the recommended values for $E_{h,av}$, $E_{h,av}$ and $E_{h,av}$ in commercial areas are twice as high as those in residential areas for the same volume of pedestrians. The lighting criteria for pedestrian ways are listed in Table 13.

Table 13. Lighting criteria for pedestrian ways in China [41].

Volume of pedestrians	Areas	$E_{h,av}$ (lx)	$E_{h,min}$ (lx)	$E_{v,min}$ (lx)
Heavy volume	Commercial area	20	7.5	4
	Residential area	10	3	2
Medium volume	Commercial area	15	5	3
	Residential area	7.5	1.5	1.5
Light volume	Commercial area	10	3	2
	Residential area	5	1	1

No references are provided in the CJJ 45-2006 standard. The explanation for this is that the standard is based on national and international studies and on practical experiences [41].

3.3 Summary

Lighting criteria for motor traffic differs from criteria for pedestrian ways due to the different visual tasks. The visual tasks of drivers include obstacle detection, the speed of detection, and the identification of the obstacle [2]. Visual tasks for pedestrians include visual orientation and facial recognition, whereas safe movement and feeling of security are also important [38].

The lighting criteria for motor traffic lighting include the average road surface luminance (L_{ave}), the overall uniformity of the luminance (U_o), the longitudinal uniformity of the luminance (U_l), the threshold increment (TI) and the surround ratio (SR) [5, 7, 9, 10]. The lighting criteria for pedestrian way lighting include the horizontal illuminance (E_h), the vertical illuminance (E_v), the hemispherical illuminance (E_{hs}), and the semi-cylindrical illuminance (E_{sc}) [6–10]. For motor traffic, a value of 2 cd/m^2 is the recommended highest average luminance level. This value was obtained from three experiments done by Dunbar (1938), de Boer (1951) and de Boer, et al. (1959) [42–44].

Uniformity, including U_o and U_l, is considered in recommendations for visual perception and for economic and cost-benefit reasons. *TI* is quantified using the equivalent veiling luminance; this is done in order to minimise disability glare [5]. *SR* is used to provide sufficient lighting for the surrounds along either side of the road, which helps motorists perceive the environment and adjust their speed in time [10].

Lighting criteria for pedestrian ways include the lighting of horizontal and vertical surfaces. The lighting of horizontal surfaces is evaluated using both average ($E_{h,av}$) and minimum ($E_{h,min}$) values for horizontal illuminance. The purpose behind the lighting of horizontal surfaces is to ensure the safe movement of pedestrians [10]. The lighting of vertical surfaces is evaluated using E_v, E_{hs} and E_{sc}. The purpose behind the lighting of vertical surfaces is to detect vertical surfaces and enable facial recognition. The recommended light levels are based on studies conducted in the 1970s and 1980s. In China, the national standard CJJ 45-2006 is applied in lighting design for urban roads and footways. The lighting criteria for pedestrian ways include $E_{h,av}$, $E_{h,min}$ and $E_{v,min}$.

4. Case study on pedestrian way lighting

This case study is based on the currently ongoing task of the CIE JCT-1 *Implementation of CIE 191 System for Mesopic Photometry in Outdoor Lighting*, which is investigating adaptation and viewing conditions and defining visual adaptation fields in outdoor lighting. The definition of the visual adaptation field is needed for the implementation of mesopic photometry, which in turn will impact the lighting recommendations and dimensioning of pedestrian ways. Data must be collected by measuring illuminances and luminances and eye-fixations at various outdoor lighting installations, such as motor traffic and pedestrian way lighting.

This study was carried out in September 2012 in Chongqing, China, in co-operation with Chongqing University and it focused on pedestrian way lighting. An eye-tracking system with SMI (SensoMotoric Instruments) iView X HED was used to record eye fixation data and the data was analysed using BeGaze software to define eye fixation areas and locations. A questionnaire survey helped in analysing the relationship between pedestrian way lighting and user preferences. Illuminance and luminance meters were used to measure the lighting conditions of the pedestrian ways.

4.1 Illuminance and luminance measurements

The measurements were made along the Sixian Road pedestrian way in Chongqing, China (Figure 6). The lighting was provided by LED luminaires, which had replaced high pressure sodium (HPS) lamps in 2011. The parameters of the lighting installation are given in Table 14. The University Town in Chongqing is a developing area; thus, the traffic was not heavy on the road during the time of the experiment. The pavement along the pedestrian way was made of cement.

The illuminance (horizontal and semi-cylindrical illuminance) and luminance measurements were carried out in the evening between 19:30 p.m. and 22:30 p.m. The weather was cloudy. The area of the measurements was between two poles, with the pole spacing being 30 m and the width of the area being 3 m. Thirty measuring points were spaced evenly in this field according to the EN 13201-3: 2003 report, *Road Lighting: Calculation of Performance*, as shown in Figure 7 [77]. The direction of luminance measurements was from west to east.

Figure 6. Pedestrian way (Sixian Road) in University Town in Chongqing, China

Table 14. Information on the LED luminaire installation along Sixian Road in Chongqing*

Location	Sixian Road, Chongqing, China
Date of installation	2011
LED luminaire	LM-DL1015-135W
Luminaire power	135 W
Luminous flux of the luminaire	11 000 lm
Luminous efficacy of the luminaire	>80 lm/W
Correlated colour temperature	5 500～6 000K
CRI	≥70
Pole height	10 m
Pole spacing	30 m

(*Data was provided by Streetlamp Management Office, Beibei District, Chongqing.)

The XYI-III illuminance meter, manufactured by Mydream Electronic in China, was used for this study (Figure 8a). The accuracy of this illuminance meter is prior to ±4%. Another illuminance meter that was used was the XYI-III semi-cylindrical illuminance meter produced by Yiou Electronic in China (Figure 8b). The luminance meter was the LM-3 luminance meter produced by Everfine in China (Figure 8c).

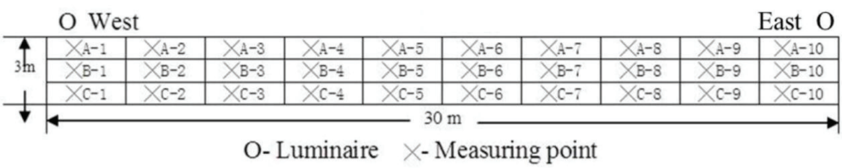


Figure 7. Measuring points along the pedestrian way

The horizontal illuminance was measured along the road surface and the semi-cylindrical illuminance at a height of 1.5 m (the photocell faced both eastward and westward at each measuring point). The height of the luminance meter was 1.5 m and the aperture was 1°. The measurement results are shown in Table 15. The average illuminance was 13.9 lx and the average semi-cylindrical illuminance values were 6.0 lx and 5.4 lx in the eastward and westward directions, respectively. The average road surface luminance was 0.49 cd/m².

a b c

Figure 8. Meters used in the study: illuminance meter (a); semi-cylindrical illuminance meter (b); luminance meter (c)

Table 15. The values for horizontal illuminance (E_h, lx), semi-cylindrical illuminance (E_{sc}, lx) (both eastward and westward) and road surface luminance (L, cd/m^2)

Date: 28.9.2012				Time: 19:30-22:30			Weather: Cloudy			Place: Sixian Road		
Direction: West-East				Pavement: Cement			Lighting conditions: see Table 14					
Pedestrian volume: Light							Traffic volume: Light					
Plants along the sidewalk: Yes							Business or advertising: No					
	E_h (lx)			**E_{sc} (lx)(Eastward)**			**E_{sc} (lx)(Westward)**			**L (cd/m^2)**		
Rows / Columns	A	B	C	A	B	C	A	B	C	A	B	C
1	5.63	15.52	10.11	4.53	3.78	4.08	4.71	4.23	4.57	0.150	0.565	0.412
2	2.52	13.57	11.41	3.53	3.72	3.31	2.43	5.71	4.95	0.064	0.500	0.405
3	14.78	14.63	12.12	3.80	3.22	3.45	8.03	6.67	5.70	0.462	0.432	0.302
4	14.99	15.18	13.96	5.82	4.22	3.25	7.11	7.97	6.51	0.632	0.629	0.420
5	18.95	16.88	14.17	10.00	8.42	5.59	11.02	9.56	6.95	0.778	0.663	0.556
6	16.78	16.70	14.79	10.27	9.21	7.81	10.16	8.02	5.49	0.718	0.632	0.486
7	16.27	13.71	10.19	8.99	7.46	6.62	5.95	4.49	3.31	0.768	0.633	0.439
8	15.42	13.89	11.45	8.25	6.90	6.19	3.41	2.93	2.95	0.579	0.433	0.347
9	18.47	15.21	12.66	8.14	6.80	6.14	3.46	2.82	2.87	0.502	0.440	0.345
10	16.44	18.18	13.14	5.78	6.15	5.40	2.96	3.65	3.10	0.526	0.464	0.355
Average value	13.9			6.0			5.4			0.49		

4.2 Eye-tracking measurements

Five subjects (two male and three female) participated in the eye-tracking experiment. The SMI iView X HED eye-tracking system (by SensoMotoric Instruments (SMI)) was used. The system consists of an eye-tracking camera system and an iView X workstation. Figure 9 shows how the eye-tracking camera system can be installed in a helmet [78]. The camera system records video about the environment. The iView X workstation runs the iView X software and contains the hardware components that enable the system to capture eye movements. This workstation controls all of the camera equipment and processes the eye and scene video signals. The iView X workstation is used to set up an experiment, control the eye-tracking camera system and trigger events, such as calibration, drift correction, and start and stop recording [79].

Calibration is essential before data recording. For this experiment, each subject was asked to take a 5-point calibration with a standard pupil diameter of 5 mm. After calibration, video with a resolution of 752 × 480 pixels was recorded together with the eye movements.

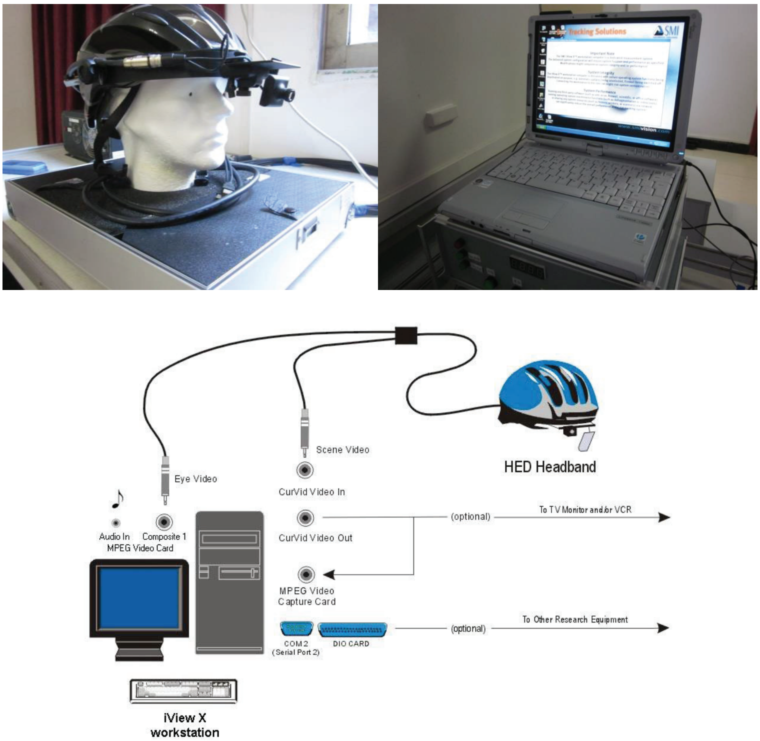


Figure 9. SMI iView X eye-tracking system [78]

4.2.1 Experimental set-up

Eye-tracking data were collected from five subjects while they were walking along the pedestrian way, first in one direction and then back in the other direction. All of the subjects walked in a straight path along the central line. The subjects walked along the pedestrian way first for the eye-tracking measurements and then again for filling in the questionnaire.

The eye-tracking data was analysed using BeGaze software. This is a software programme designed for behavioural gaze analysis that measures visual attention, reveals visual search patterns or quantifies fixation/saccade parameters, such as amplitude or latency [80]. The videos and samples recorded using the eye-tracking system can be loaded into this software programme using fast selection, preview and exporting data options. The results show the visual and analytical data for eye gaze and eye movements as well as the pupil data [80]. The features of BeGaze software contain scan paths, areas of interest (AOIs), statistical data and quantitative analysis of fixation, saccade, blink and pupil areas.

The procedure for using the BeGaze software involved defining reference views in the custom trial selector and mapping fixation points for semantic gaze mapping. In this study, eight reference views were defined for a selected number of walking distances in both eastward and westward directions. The pedestrian way was divided into six sections, with each section being 5 m long. The first and the last sections were excluded from the analysis. The four sections in the middle (from 5 to 10 m, 10 to 15 m, 15 to 20 m and 20 to 25 m) are shown in Figure 10 and Figure 11. The scan paths of the subjects in each reference view were produced by the mapping fixation points. Gridded AOIs (areas of interest), including dwell time and the fixation counts, were recorded.

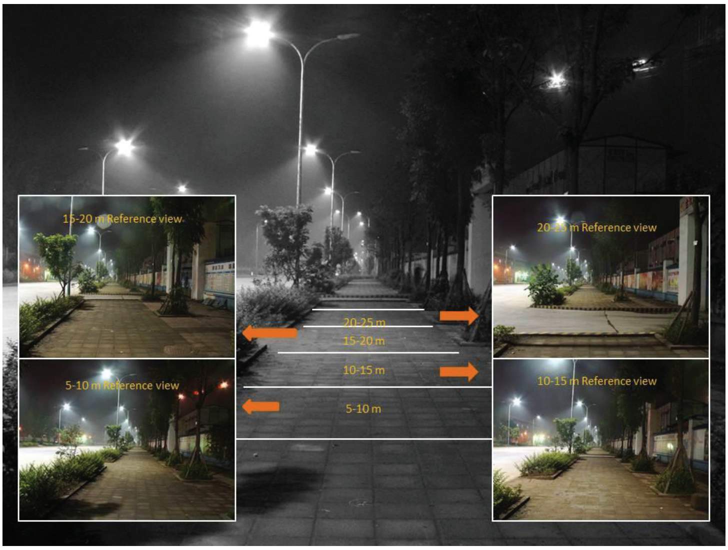


Figure 10. Reference views in the eastward direction

Figure 11. Reference views in the westward direction

4.2.2 Results

Scan paths

Scan paths show the gaze positions and eye-tracking routes of the selected reference view. Figure 12 and Figure 13 show complete data for one subject in eight reference views for a fixation and saccade plot with a dynamic fixation radius. The fixation radius is related to the duration of the fixations. When the duration of the fixations is longer, then the fixation radius is larger. Most of the fixations are concentrated along the road surface.

Figure 12. Scan paths of one subject in the sections of 5-10 m, 10-15 m, 15-20 m and 20-25 m when walking in an eastward direction

When recording the eye-tracking data, one of the five subjects experienced a recording error; so that particular data was excluded from the analysis. Figure 14 shows examples of a fixation and saccade plot with a dynamic fixation radius in the same reference view for four subjects. This reference view is for the 10 to 15 m section in the westward direction. The L_{ave} in this area was 0.59 cd/m^2 (Table 15). The fixation areas and locations of each subject were close to the central area of the road surface at the horizontal level but spread over a wider area at the vertical level.

Figure 13. Scan paths of one subject in the sections of 5-10 m, 10-15 m, 15-20 m and 20-25 m when walking in a westward direction

Figure 14. Scan paths of one reference view (the 10 to 15 m section in the westward direction) for four subjects.

Gridded AOIs

It is impossible to avoid blinking when recording the eye-tracking data. Thus, the fixation counts and dwell times are not continuous but jumpy in the recorded videos, and data can only be recorded when the eyes are open.

The software automatically grids the AOIs in each of the eight reference views. Figure 15 and Figure 16 show an example of how total dwell times and fixation counts in one reference view (10 to 15 m westward walking path) for the four subjects were described using a grid of AOIs based on the amount of attention received. The image shows an 8 × 8 grid. The dwell time, which has a measuring unit of milliseconds (ms), is the sum of all fixations within an AOI for a selected reference view; the fixation count is the number of all fixations for the selected subjects [81]. Each grid with a different colour describes the different levels of attention paid to each image. The grid that received the most attention is marked in red.

Figure 17 shows the areas with the highest values with respect to dwell times for four subjects (S1 to S4) in the reference view (10 to 15 m walking path in a westward direction). Figure 18 describes the areas with the highest values in terms of fixation counts for four subjects (S1 to S4) in the same reference view (10 to 15 m walking path in a westward direction). Figures 17 and 18 indicate that the longest dwell times in the areas did not necessarily have the most fixation counts. For example, Subject 1 (S1) had the highest fixation count (2 times) in two areas (Figure 18), but only one of those two areas had the longest dwell time, 618.5 ms (Figure 17). In turn, Subject 4 (S4) had the longest dwell time of 2134.2 ms in one area, but the highest fixation count was in another area.

Figure 15. Dwell times (ms) of one reference view (10 to 15m westward) for four subjects.

Figure 16. Fixation counts of one reference view (10 to 15m westward) for four subjects.

Figure 17. The highest values with respect to dwell times (ms) for four subjects (S1 to S4) in the reference view (10 to 15 m walking path in a westward direction)

Figure 18. The highest values in terms of fixation counts (times) for four subjects (S1 to S4) in the reference view (10 to 15 m walking path in a westward direction)

4.3 Questionnaire

4.3.1 Experimental set-up

Five subjects were asked to take a colour vision test and a visual acuity test indoors before the experiments. The colour vision test used a method developed by Kechang Wang [82]. The visual acuity test used the Lea numbers near vision chart.

The questionnaire consisted of two parts: basic information and questions (Appendix 2). The basic information pertained to the gender, age and studying/working field of the subjects as well as the results from their visual acuity check and colour vision test, and information about how often they walk along the street used in the study. The ages of the five subjects ranged from 25 to 35 years. Their studying/working fields were all related to construction. All of the subjects reported that they were walking along the street in question for the first time. The questions part of the questionnaire included ten questions that focused on the subject's general feeling when walking along this particular street; how they felt about the pavement; the lighting conditions, including the light level, light distribution, the colour of the light, and glare; whether or not they felt safe; and facial recognition (Appendix 2). One example of the questions is shown in Table 16.

Table 16. Sample question from the questionnaire

10. How do you generally feel when walking along this street after dark?						
Not comfortable at all	☐ –2	☐ –1	☐ 0	☐ 1	☐ 2	Very comfortable

4.3.2 Results

The subjects gave their answers in the questionnaire using a five-point-scale. The questionnaire answers were transformed in to weighted average values for the evaluation:

$$V=\left[\sum_{i=1}^{n} W_i T_i\right] / \sum_{i=1}^{n} W_i \qquad (n=1,2,3,4,5) \qquad (1)$$

Where V is the evaluation value; T_i represents the values for each question in the range of [-2, -1, 0, 1, 2]; and W_i is the number of subjects who chose the according value (T_i). The results are shown in Table 17.

The purpose of lighting for pedestrian ways is to increase feeling of safety and to enable facial recognition [8, 10]. The light level is important for feeling of safety; the uniformity of the lighting, control of glare, and colour rendering are also important [10]. In addition, facial recognition can be quantified using the values for minimum vertical illuminance and semi-cylindrical illuminance [10].

According to the CIE 115: 2010 report, the values for $E_{h,av}$ and $E_{h,min}$ provide the lighting criteria for pedestrian ways. In addition, the values obtained for $E_{v,min}$ and $E_{sc,min}$ also enable facial recognition. Table 18 summarises the relationship between the parameters given in the lighting recommendations [6–10], the characteristics of the pedestrian way under study and the questionnaire results (value of evaluation, V).

Table 17. The results of the questionnaire

Questions	Values for each question (Ti)					Evaluation (V)
	-2	**-1**	**0**	**1**	**2**	
1. Feeling about the pavement	0	2	0	3	0	0.2
2. Feeling about the light level	0	4	1	0	0	-0.8
3. Feeling about the lighting distribution	1	1	1	2	0	-0.2
4. Feeling about the colour of the light	0	2	2	1	0	-0.2
5. Glare	No glare					-
6. Feeling about walking after dark	0	3	1	1	0	-0.4
7. Importance of lighting for movement	0	0	0	1	4	1.8
8. Importance of lighting for safety	0	0	0	0	5	2.0
9. Feeling about facial recognition	1	1	1	1	1	0
10. General feeling about walking along this street	0	2	1	1	1	0.2

Table 18 shows that the subjects assigned a value of 0.2 to the pavement (V), which means that they were almost neutral in their opinions about the pavement material. Lighting for safety and movement were admittedly important based on the values assigned to it in questions 7 and 8. The average horizontal illuminance of the pedestrian way was 13.9 lx, which the subjects regarded as being somewhat unsatisfactory (V= -0.8). Meanwhile, they felt that the uniformity of lighting and colour rendering were quite satisfactory (V= -0.2). None of the subjects felt that glare was an issue. The measured value for the minimum semi-cylindrical illuminance ($E_{sc,min}$) was 2.43 lx, which constituted a neutral value on the part of the subjects (V =0). It seems that the subjects did not pay much attention to facial recognition because of the light volume of pedestrians or because the pedestrian way was wide enough so that people could walk side by side without having much of a need to identify others. In conclusion, the subjects did not have negative reactions to the lighting conditions of the pedestrian way.

Table 18. Relationship between the lighting parameters and questionnaire results.

Questions	Lighting parameters in CIE, 2010		Lighting criteria in CIE, 2010		Characteristics of the pedestrian way	Evaluation V
1. Feeling of pavement		Pavement			cement	0.2
2. Feeling of light level	Horizontal illuminance, E_h	Feeling of safety	P1	15 lx	13.9 lx	-0.8
			P2	10 lx		
3. Feeling of lighting distribution	Uniformity, U_o				0.2	-0.2
4. Feeling of colour of light	Colour rendering				≥70	-0.2
5. Glare	Glare				NO	-
6. Feeling of walking after dark						-0.4
7. Importance of lighting for movement						1.8
8. Importance of lighting for safety						2.0
9. Feeling of facial recognition	Minimum semi-cylindrical illuminance, $E_{sc,min}$	Facial recognition	P1	3 lx	2.43 lx	0
			P2	2 lx		
10. General feeling of walking on this street						0.2

4.4 Summary

The pedestrian way experiment consisted of luminance and illuminance measurements, eye-tracking measurements, and a questionnaire for the subjects. For this pedestrian way, the average horizontal illuminance ($E_{h,av}$) was 13.9 lx, which fulfils the requirements for the P2 class (10 lx) and is close to those for the P1 class (15 lx) in the CIE recommendations [10]. The value of 13.9 lx for E_h meets the recommendation of 10 lx in the Chinese guidelines [41].

The SMI iView X HED eye-tracking system was used for the eye-tracking measurements. The eye-fixation areas and locations of the subjects were close to the central area of the road surface at the horizontal level, but they were spread over a wider area at the vertical level. When analysing the eye-tracking data, it is important to take both the dwell times and fixation counts into account. The areas with the longest dwell times are not necessarily equal to the areas with the most fixation counts.

For this pedestrian way, the $E_{h,av}$ was 13.9 lx, which was regarded as a bit low because of the fact that user preferences were not so satisfied. The minimum semi-cylindrical illuminance ($E_{sc,min}$) was 2.43 lx, which constituted a neutral evaluation, the subjects did not pay much attention to facial recognition. The reason may have to do with the light volume of pedestrians and a wide walking path, which made people walk side by side without needing to identify other people approaching them.

5. Discussion

Reviewing all of the recommendations in the CIE and CEN publications for lighting of motor traffic and pedestrian ways indicates that the experimental basis for the criteria regarding motor traffic lighting is from the 1930s to 1950s, while the basis for the criteria regarding pedestrian way lighting was created in the 1970s and 1980s. New experiments are needed due to recent developments in lighting techniques and research facilities.

The case study used eye-tracking measurements to assess the viewing and adaptation conditions of pedestrians. The questionnaire survey indicated a relationship between lighting conditions and user preferences along the pedestrian way. Facial recognition was not important along this particular pedestrian way because the light volume of pedestrians and the width for the pedestrian way caused people to walk side by side without needing to identify other passer-by.

5.1 Lighting criteria for motor traffic

For motor traffic lighting, the CIE and CEN publications [5, 7, 9, 10] recommend a value of 2 cd/m^2 as the minimum average road surface luminance level for the highest lighting class. The CIE publication No. 12.2 was the first study to make recommendations for motor traffic lighting [5]. In this study, the core references were the experiments done by de Boer in 1951 and de Boer et al. in 1959. In addition, the study done by Dunbar in 1938 was the first to suggest a value of 2 cd/m^2 as the highest average luminance level. However, there is no information in the CIE study about how the values for road surface luminance lower than 2 cd/m^2 were determined for the lower lighting classes. Thus, the basis for the average road surface luminance for the lower lighting classes is unknown and it lacks experimental work. Moreover, the experimental set-up in these studies does not meet the conditions for current motor traffic lighting, differing among other things in the types of light sources that were used. They also have deficiencies in terms of the number of subjects and the age distribution of the subjects.

The types of light sources used in the experiments [42–44] are inconsistent with the ones used in modern road lighting. In contemporary road lighting installations, HPS lamps and high pressure mercury (HPM) lamps are mainly used. A report from 2007 [83] shows the percentages of light sources used in

Europe as 47% HPS lamps, 32% HPM lamps, 9% LPS lamps, 8% CFLs, and 3% MH lamps. However, the experiment done by de Boer in 1951 only used incandescent lamps, whereas the experiments done by de Boer et al. in 1959 used LPS lamps, incandescent lamps, fluorescent and colour-corrected HPM lamps. The light spectra of these lamps are different. The visibility tests done by de Boer et al. in 1959 showed that visibility distance was affected by the lamp spectrum: sodium lamp lighting provided more favourable results than colour-corrected mercury lamps under the same road surface luminance conditions [44].

One experiment conducted by de Boer et al. [44] found that a value of 1.5 cd/m² would serve as a '*good*' luminance level for the average road surface luminance recommendation. However, only 16 subjects participated in this experiment. It can be questioned whether the number of subjects was sufficient to reach such critical conclusions for a subjective test.

The average age of the subjects in the experiments conducted by de Boer et al. [43, 44] was between 25 and 30 years (Table 2). However, 2009 statistics from the US Department of Transportation reveal that the 45–49 year old group and the 50–54 year old group contain the largest share of drives in the US. It is known that several ocular and retinal disorders are strongly correlated with increasing age [84]. Thus, it can be questioned whether the results obtained in these experiments would provide an adequate amount of lighting for older drivers.

All of the experiments and studies for establishing the recommendations and defining the lighting classes for motor traffic lighting have been done on the basis of photopic photometry. The values for average road surface luminance in the recommended lighting classes range from 0.3 cd/m² to 2 cd/m² (Table 1). However, luminance levels between 0.005 cd/m² and 5 cd/m² are in the mesopic range [2]. Thus, the system for mesopic photometry should be applied when conducting the experiments and preparing the studies. Moreover, all of the experiments [42–44] were conducted based on central vision (Table 2). For central viewing, mesopic and photopic photometry match well. However, for peripheral vision, which is relevant when driving, mesopic photometry should be used [2]. Thus, new experiments and studies are needed for defining recommendations for motor traffic lighting on the basis of the system for mesopic photometry.

5.2 Lighting criteria for pedestrian ways

For pedestrian way lighting, the CEN and CIE publications provide recommended illuminance values for different lighting classes. The values for $E_{h,av}$, including 1 lx to 2 lx, 2 lx to 3 lx, 5 lx, 15 lx and 20 lx, are based on studies conducted during the 1970s and 1980s (Table 8). A minimum horizontal illuminance of 1 lx was deduced from a study on emergency lighting [51, 64–67]. However, no information or single study adequately explained the basis for recommending these values. The only explanation was that the values for $E_{h,av}$ recommended in the CEN publication EN 13201-2:2003 are higher than similar recommendations in Australia, New Zealand (0.5 lx to 7 lx) and Japan (3.0 lx to 5.0 lx) [32].

The values for $E_{v,av}$ range from 0.5 lx to 50 lx in the EN 13201-2: 2003 report, but from 0.6 lx to 5 lx in the CIE 115:2010 report. The explanation for the difference has to do with the different visual tasks; according to the EN 13201-2:2003 report, the values are for observing vertical surfaces, whereas in the CIE 115:2010 report they are for facial recognition. However, the needs pertaining to facial recognition can be specifically quantified using the values for $E_{sc,min}$, with the values ranging from 0.4lx to 3 lx [10]. Hence, the explanation given in the CIE 115: 2010 report may be somewhat imprecise.

Photopic photometry was used as the basis for meeting the recommendations and defining the lighting classes for pedestrian way lighting. The recommended illuminance values, for example, for $E_{h,av}$ values ranging from 2.0 lx to 15 lx in the EN 13201-2:2003 report (Table 7), imply that the corresponding values for photopic luminance should fall in the range of 0.04 cd/m^2 to 0.33 cd/m^2 with a given surface reflectance of 0.07 (typical of asphalt) [37]. This means that the vision of pedestrians is usually in the mesopic range when walking at night. As a result, the system of mesopic photometry should also be applied for pedestrian way lighting recommendations.

5.3 Case study on pedestrian way lighting

In this study, an eye-tracking system was attached to a helmet worn by the subjects. The helmet needs to be fitted firmly on the head after calibration. This may limit the behaviour of subjects, meaning that the experimental conditions will not quite correspond to actual conditions. There is another choice: to wear eye-tracking glasses to record data while walking, where the subjects might feel more natural while recording the data.

It was difficult for the subjects to avoid blinking while recording the data, thus, the fixation counts and dwell times were not continuous. However, the measurements illustrated that most of the fixation areas and locations focused on the road surface. The fixation areas and locations were close to a central area of the road surface at the horizontal level, but they were spread over a wider area at the vertical level. Dwell times and fixation counts need to be considered at the same time when analysing the eye-tracking data. The study demonstrated that the areas with the longest dwell times were not necessarily equal to the areas with the most fixation counts. The conclusion is that both the dwell times and fixation counts need to be taken into account when using AOIs to study the visual adaptation field. Moreover, further studies could combine eye-fixation data with pupil size and luminance data. Changes in the size of the pupil can be also recorded using the eye-tracking system, since the lighting levels affect pupil size. This would help when analysing the visual adaptation fields of road users.

The average horizontal illuminance of the pedestrian way was 13.9 lx, which fulfilled the requirements for the S2 class (10 lx) and was close to those for the

S1 class (15 lx) in the CEN publication EN 13201-2:2003 [9]. It also met the recommended value of 10 lx in the Chinese CJJ 45-2006 guidelines [41]. The questionnaire survey indicated that people consider pedestrian way lighting to be important for movement and safety. All of the subjects were neutral in their opinions about the relative ease/difficulty of facial recognition. This conclusion supports the results from the study by Davoudian and Raynham [32], where pedestrians felt less insecure and spent more time looking at the road surface when the horizontal illuminance met the S1 class of the EN 13201-2:2003 report. This study does not support the conclusions presented by Caminada and van Bommel [73], who argued that facial recognition requires high light levels and is essential for providing a sense of security when encountering other pedestrians. As a result, the importance of facial recognition depends on the specific visual tasks at different light levels along pedestrian ways.

This was a preliminary study on using eye-tracking measurements to study visual adaptation conditions. Future studies will need to use more subjects.

6. Conclusions

The purpose of the lighting criteria for road and pedestrian ways is to make the objects on the road visible without causing discomfort to drivers or pedestrians. The current lighting recommendations for motor traffic give values for average road surface luminance, overall luminance uniformity, longitudinal luminance uniformity, threshold increment, and surround ratio. The current lighting recommendations for pedestrian ways give values for average and minimum horizontal illuminance, hemispherical illuminance, overall uniformity of hemispherical illuminance, average vertical illuminance, and minimum semi-cylindrical illuminance.

The recommended values in the CIE and CEN publications are mostly based on research performed no later than in the 1980s or else they completely lack scientific data. The fundamental experiments that recommended a value of 2 cd/m^2 for the average road surface luminance in road lighting were conducted in the 1930s and 1950s [42–44]. For the most part, studies done in the 1970s and 1980s form the basis for the recommended values for horizontal illuminance and semi-cylindrical illuminance in pedestrian way lighting. All of the above studies were conducted using foveal vision based on photopic photometry, yet the luminances of road and pedestrian way lighting are mostly in the mesopic range. Thus, mesopic photometry based on peripheral vision should be used, even though photopic photometry is also applicable at low light levels for foveal viewing. In addition, the light sources used in the experiments underpinning the current lighting recommendations include low pressure sodium lamps, colour-corrected mercury lamps and incandescent lamps. Nowadays, light sources with white light, such as LEDs and MH lamps, are increasingly being used in both road and pedestrian way lighting. White light is favoured by the system for mesopic photometry. As a result, new experiments and studies are needed to define recommendations for motorized and pedestrian way lighting on the basis of the mesopic photometric system. Visual adaptation field studies are needed in order to develop guidelines for implementing mesopic photometry.

A case study in pedestrian way was conducted in Chongqing of China to investigate visual adaptation field and user preferences. A questionnaire was used to assess the relationship between lighting conditions and user preferences. The light level along this pedestrian way did not satisfy the subjects involved in the experiment. The subjects concentrated on the pavement but not on facial recognition. The reason for this may be the light volume of pedestrians and the width of the walking path. In visual adaptation field studies, eye-tracking measurements are needed to define eye-fixation areas and locations. Currently, the eye-tracking systems are set up with helmet or glasses. Eye-tracking data, such as fixation counts and dwell times, are recorded using the eye-tracking systems. The data are described using gridded AOIs. Both fixation counts and dwell times need to be considered when using AOIs to study the visual adaptation field. In this study, most of the fixation areas and locations focused on the road surface; the fixation areas and locations are close to a central area at the horizontal level, but they are spread over a wider area at the vertical level.

In further studies, eye-tracking data should be combined with pupil size and luminance data. This would provide facilities for investigating adaptation conditions in outdoor lighting and when defining adaptation luminances.

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Appendix 1

Summary of lighting classes for motor and pedestrian way based on CIE, 1977; CIE, 1992; CIE, 1995; CIE, 2000; CEN, 2003 and CIE, 2010

Publications	Lighting classes	Parameters
CIE 12.2:1977	A, B, C, D, E	traffic volume, traffic speed, traffic composition
CIE 92:1992	City or Town Centres (Mixed and Ped. *), Suburban Shopping Streets (Mixed and Ped.), Village Centres (Mixed and Ped.)	traffic volume , traffic composition, the need to preserve the character of the environment, facial recognition
CIE 115:1995	M, P**	function of the road, traffic density, traffic complexity, traffic separation, existence of facilities for traffic control, the need to preserve the character of the environment, crime risk, visual guidance, facial recognition
CIE 136:2000	P1, P2, P3, P4, P5, P6, P7	traffic volume by pedal cyclists or pedestrian, the need to preserve the character of the environment, crime risk, visual guidance, facial recognition
EN 13201-2:2003	M, S, A, ES, EV***	speed, separation of carriageways, traffic volume, ambient luminance, visual guidance/traffic control, facial recognition
CIE 115:2010	M, C, P****	speed, traffic volume, traffic composition, separation of carriageways, intersection density, parked vehicles, ambient luminance, visual guidance/traffic control, facial recognition

*Mixed: mixed vehicle and pedestrian; Ped.: wholly pedestrian.
**M: motorised traffic, P: pedal cyclists or pedestrians.
Subclasses for M: M1, M2, M3, M4 and M5.
Subclasses for P: P1, P2, P3, P4, P5, P6, P7.
***M: motorised traffic, S and A: pedestrians and pedal cyclists, ES: additional classes for pedestrian areas for the purposes of reducing crime and suppressing feelings of insecurity, EV: addition classes in situations where vertical surfaces need to be seen.
Subclasses for M: ME1, ME2, ME3 a, ME3 b, ME3 c, ME4 a, ME4 b, ME5 and ME6.
Subclasses for S: S1, S2, S3, S4, S5, S6 and S7.
Subclasses for A: A1, A2, A3, A4, A5 and A6.
Subclasses for ES: ES1, ES2, ES3, ES4, ES5, ES6, ES7, ES8 and ES9.
Subclasses for EV: EV1, EV2, EV3, EV4, EV5 and EV6.
**** M: motorized traffic, C: conflict areas, P: pedestrians.
Subclasses for M: M1, M2, M3, M4, M5 and M6.
Subclasses for P: P1, P2, P3, P4, P5, P6.

Appendix 2 Translation of Questionnaire in Chinese

Questionnaire

Date: Time:
Place:
Pavement material: Cement □ Marble □ Stone and slabs □ Other:
Light sources: HPS □ MH □ LED □ Other:
Note:

***The above information is not shown for the subjects.**

Basic information

Gender: Male □ Female □
Age:
Studying/Working field:
Visual acuity check: Normal □ Abnormal □
Colour vision test: Normal □ Abnormal □
I walked the street, the first time today. □
few times a year. □
few times a month. □
few times a week. □
every day. □

Questions

1. How do you feel about the pavement of this street?

Not comfortable at all	□	□	□	□	□	Very comfortable
	–2	–1	0	1	2	

2. How do you feel about the lighting on this street?

Too dark	□	□	□	□	□	Too bright
	–2	–1	0	1	2	

3. How do you feel about the lighting distribution on this street?

Not uniform at all	□	□	□	□	□	Very uniform
	–2	–1	0	1	2	

4. How do you feel about the colour of light on this street?

Not comfortable at all	□	□	□	□	□	Very comfortable

–2 –1 0 1 2

5. Do you experience glare on this street? Yes ☐ No ☐
If yes, how do you feel the glare affects you?

Not comfortable at all	☐ –2	☐ –1	☐ 0	☐ 1	☐ 2	Very comfortable

6. How do you feel when walking alone along this street after dark?

Not comfortable at all	☐ –2	☐ –1	☐ 0	☐ 1	☐ 2	Very comfortable

7. How important do you feel lighting for moving easily on this street after dark?

Not important at all	☐ –2	☐ –1	☐ 0	☐ 1	☐ 2	Very important

8. How important do you feel lighting for feeling of safety on this street after dark?

Not important at all	☐ –2	☐ –1	☐ 0	☐ 1	☐ 2	Very important

9. How do you find facial recognition on this street after dark?

Not easy at all	☐ –2	☐ –1	☐ 0	☐ 1	☐ 2	Very easy

10. How do you generally feel when walking along this street after dark?

Not comfortable at all	☐ –2	☐ –1	☐ 0	☐ 1	☐ 2	Very comfortable

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Lighting criteria for road and pedestrian ways is to make the objects on the road visible without causing discomfort to the drivers or the pedestrians. The basis of recommended values in the CIE and CEN publications is mainly the research conducted in foveal vision based on photopic photometry. New experiments and studies are needed for defining recommendations for the motorized and pedestrian way lighting on the basis of the mesopic photometric system. Visual adaptation field studies are needed in order to develop guidelines for implementing mesopic photometry.The visual adaptation fields studies are currently based on the eye-tracking systems. Eye-tracking data is recorded such as fixation counts and dwell times. The data are described in gridded AOIs. In further studies, eye-tracking data should be combined with pupil size and luminance data. This would provide facilities for investigating adaptation conditions in outdoor lighting and in defining adaptation luminances.

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